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THE ENERGY EXPENDITURE AND MECHANICAL ENERGY DEMAND IN WALKING

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1. The energy expenditure, the vertical lift work of the trunk per step, and the leg and foot lengths have been measured for 11 young male subjects walking on a horizontal treadmill at 1–4 m.p.h. at natural step frequency and in some instances at controlled frequencies and up and down hill. Similar measurements have been made whilst box stepping. These data and others from the literature have been analysed.

2. The vertical lift per step (L) is a geometric function of the lengths of the leg, foot and pace (R, d and P respectively) such that $L=(P-d)^2/8R$.

3. The energy expenditure of walking at natural step frequency on the horizontal treadmill is linearly related to the vertical lift work which is the product of lift per step, step frequency and body weight.

This relationship does not hold at arbitrary step frequencies above and below those chosen spontaneously. Under these circumstances the energy expenditure of walking at a given speed increases : by contrast the lift and the lift work decrease progressively with increasing step frequency in accordance with the geometric configuration.

However, a relationship has been developed which suggests that energy expenditure may again be a linear function of lift work when step frequency is taken into account.

The energy expenditure of uphill but not of downhill walking at natural step frequency can be described in similar terms when allowance is made for the additional vertical work. Analysis of the energy expenditure of stepping exercise suggests that, as compared with walking, a smaller proportion of the total energy is expended in vertical work.

4. The energy expenditure of horizontal walking at natural step frequency is linearly related to the square of the forward velocity (v^2). This relationship has been used to calculate the velocity of minimal energy expenditure per unit of horizontal distance moved.

The velocities so obtained, including and excluding the resting energy expenditures, are respectively $3\frac{1}{2}$ and $2\frac{1}{4}$ m.p.h. which agree with those experimentally determined. The linear extrapolation of the regression relationship gives a mean energy expenditure at zero velocity of 2·4 kcal/min which is in excess of the observed mean resting level.

5. Prediction of walking energy expenditure (E_{O_2}) has been attempted using both the lift work and velocity squared relationships. Use of the first requires knowledge both of leg and foot lengths and of the pace which the subject will adopt at a given velocity; the latter has not so far proved amenable to prediction. The second in the form $E_{O_2}/W=0{\cdot}0386\times 4{\cdot}25\times 10^{-6}\,v^2$ kcal/kg/min can be used to predict the walking energy expenditure of our subjects to within 0·7 kcal in 95 per cent of cases. Greater precision can be achieved by individual calibration of the subjects.

§ 1. Introduction

Studies of the dynamics of locomotion (Fischer 1899, Fenn 1930, Elftman 1944, Eberhart and Inman 1951) show that body dimensions, particularly leg and foot lengths, determine in part the demand for energy in walking. However, few attempts have been made to assess their contribution to the rate of energy expenditure. Benedict and Murschhauser (1915) and Smith (1922) measured the vertical movement of the body whilst walking on the flat but appear to have made little use of their findings.

Energy expenditure varies with body weight (Frentzel and Reach 1901, Durig and Zuntz 1904) and with step frequency (Magne 1920, Atzler and Herbst 1927). Mahadeva *et al.* (1953) found that the correlation with body weight was not improved when height and age were taken into account. However, making allowance for leg length does significantly improve the relationship (Brockett *et al.* 1956).

Prediction of energy expenditure from body weight and horizontal velocity has been attempted for subjects walking on the flat (Passmore and Durnin 1955) and uphill (Pasargiklian *et al.* 1953). The precision of these estimates is not great and probably could be improved by taking other variables into account.

In this paper we shall derive a number of relationships between the variables involved in walking, which are of theoretical and practical interest, and which provide a broader basis from which to predict energy expenditure.

Measurements were made on ten army recruits, aged 18–19 years (subjects 1–11)*, and one older subject aged 32 years (No. 12); all were familiar with the laboratory procedure including walking on a treadmill.

§ 2. Methods

The subjects, wearing walking shoes and gym clothes, walked on a motor-driven treadmill at speeds of 1, 2, 3, $3\frac{1}{2}$ and 4 m.p.h. on the flat and down a gradient of 8 per cent. In addition, subjects 2 and 12 walked at these speeds up gradients of 4, 8 and 12 per cent and subject 2 down gradients of 2, 4, 8 and 12 per cent. This subject also walked at two specified speeds and varied step frequency in time to a metronome. In addition to walking, subjects Nos. 2 and 12 also did stepping exercise on and off a box of predetermined height in time to a metronome at work levels of 70–700 kg m/min (Hugh Jones and Lambert 1952).

On the flat and downhill the subjects walked for about $1\frac{1}{2}$ hours continuously, the speed being changed while they were still walking. The uphill experiments were done in random order. All measurements were made after at least 6 min walking at any one speed, gradient or work level.

The speed of the treadmill was set approximately on a speedometer and timed precisely by an electrical contact recording on a kymograph. To limit movement of the arms and to prevent forward or backward drift along the treadmill, the subject walked between tapes stretched across the treadmill.

The vertical oscillation of the trunk, which occurs in walking, was recorded by means of a wire attached to a firmly fitting waist belt and passing upward over a pulley to a mechanical integrator, which recorded the movement of the wire in one direction only. This movement was also used to record on a kymograph the lift per step and the stepping frequency per minute. The wire was kept taut by spring loading, using a long spring to minimze changes in tension. There was good agreement between the integrator and the kymograph records ($r = 0{\cdot}99$). Expired air was measured with a dry gas meter. Samples were collected distal to a 1·75 litre mixing chamber and analysed with a micro-Scholander analyser (Scholander 1947). The composition of the samples

* Subject 3 dropped out before the present study began, but the original numbering has been retained to facilitate comparison with other published data.

was found to be representative of the mixed expired gas collected simultaneously in Douglas bags. Duplicate analyses were required to agree to within 0·04 per cent.

Anthropometric measurements were made as follows: height and stem height to the nearest 0·01 m; leg length (R) to the nearest 0·001 m, the length being measured from the upper border of the greater trochanter to the ground whilst the subject stood erect without shoes; foot length (d) to the nearest 0·001 m using calipers (for both leg and foot lengths average values for the two limbs were recorded); weight, in gym kit but without shoes, to the nearest 0·1 kg. The change of position of the centre of gravity of the body on moving the legs apart was estimated with the subject lying on a balanced horizontal platform.

2.1. *Definition of Terms*

(1) *Lift per step* (L) m. The vertical lift of the trunk as measured from the waist belt.

(2) *Lift per minute* (L_n) m/min. The total upward movement of the trunk per minute as recorded by the integrator.

(3) *Work of lift per minute* (W_L) kcal per min. The product of weight of subject and lift per minute. Converted to thermal units using the coefficient 427 kg m/kcal.

(4) *Gradient work per minute* (W_S) kcal per min. The product of body weight, treadmill belt speed and treadmill gradient as measured by the sine of its angle of incline to the horizontal. This is also converted into thermal units.

(5) *Metabolic energy expenditure* (E_{O_2}) kcal per min. This is the total oxygen consumption per minute calculated from the ventilation minute volume and analysis of expired gas and expressed in calories using a conversion factor of 4·875 kcal/l.

§ 3. Results

The main results are given in six tables. Table 1 gives the anthropometric data for the subjects and for M.A.M. and E.D.B. who were studied by Benedict and his colleagues at the Carnegie Institute; Table 2 gives the walking speed as estimated from the speedometer and accurately measured with the electrical contact on the belt; also lift, liftwork and energy expenditure for subjects 1–12.

Table 3 gives the wider range of these measurements on subject No. 2 when stepping at his spontaneously chosen frequencies; Table 4 gives the results on subjects Nos. 2 and 12 walking uphill.

Table 5 gives downhill data for subjects 1–11 on an 8 per cent incline and subject 2 on inclines of 2, 4, 8 and 12 per cent.

Table 6 brings together a number of regression relationships which are relevant to the interpretation of the findings.

3.1. *Anthropometric Relationships*

Leg length and foot length are both correlated with total body height. The relationship for foot length agrees well with that reported by Morant and

Table 1. Age, anthropometric data and resting energy expenditure for all subjects

No.	Subject	Age (years)	Weight (kg)	Height (m)	Stem height (m)	Leg length (m) (S.E. $\pm$ 0·0035)	Foot length (m) (S.E. $\pm$ 0·0018)	Vertical movement of body centre of gravity per step as percentage of movement of trunk (S.E. $\pm$ 0·846)	Resting energy expenditure (kcal/min) (S.E. $\pm$ 0·143)
1	D.C.D.	18	66·4	1·81	0·36	0·995	0·267	91·5	1·47
2	J.B.	18	68·2	1·75	0·36	0·916	0·264	87·7	1·57
4	G.J.J.	18	58·7	1·70	0·36	0·895	0·237	86·9	1·34
5	J.E.J.	18	64·5	1·76	0·36	0·906	0·275	86·8	1·37
6	J.L.M.	18	54·4	1·69	0·35	0·891	0·257	87·3	1·32
7	B.J.J.	18	52·9	1·63	0·33	0·853	0·253	87·5	1·44
8	J.D.	18	55·4	1·72	0·37	0·884	0·257	87·1	1·29
9	E.W.W.	19	61·0	1·61	0·34	0·865	0·248	85·9	1·53
10	J.C.	18	74·6	1·79	0·37	0·944	0·283	88·0	1·62
11	J.D.A.F.	18	59·0	1·71	0·36	0·879	0·261	87·9	1·31
12	J.E.C.	32	61·8	1·82	0·36	0·973	0·263	90·1	1·12
13	M.A.M.	32	71·5	1·76	—	—	—	—	1·25
14	E.D.B.	23	57·0	1·73	—	—	—	—	1·08

Table 2. Lift work and energy expenditure of walking on the horizontal treadmill

Subject	Walking speed (m.p.h. approx.)	Walking speed (m/min)	Frequency (steps/min)	Lift (m/min)	Lift work (kcal/min)	Energy expenditure (kcal/min)
1	1	27·0	55	0·47	0·07	3·14
	2	52·9	69	1·84	0·28	3·73
	3	78·2	92	4·21	0·66	4·31
	3½	92·7	105	4·99	0·78	4·85
	4	103·9	112	5·77	0·90	5·68
2	1	25·9	59	0·35	0·06	2·71
	2	52·6	84	1·62	0·26	3·24
	3	78·1	104	3·60	0·57	4·01
	3½	94·8	114	4·98	0·79	4·79
	4	106·0	122	6·39	1·01	5·68
4	1	24·6	54	0·30	0·04	2·37
	2	54·8	83	1·25	0·17	3·36
	3	80·1	111	3·17	0·43	3·82
	3½	91·6	127	3·94	0·54	5·01
	4	106·7	132	6·10	0·83	5·39
5	1	28·0	64	0·42	0·06	2·69
	2	53·9	83	1·56	0·23	3·26
	3	81·6	107	3·27	0·49	4·37
	3½	92·7	117	3·46	0·52	4·71
	4	105·4	123	6·22	0·94	5·86
6	1	26·1	54	0·26	0·03	2·07
	2	52·9	78	1·53	0·19	2·71
	3	78·0	103	2·90	0·37	3·24
	3½	90·6	116	3·89	0·50	3·87
	4	105·9	130	4·69	0·60	4·29
7	1	28·2	74	0·27	0·03	2·12
	2	54·8	99	1·24	0·15	2·69
	3	79·6	116	2·64	0·33	3·31
	3½	91·0	122	3·49	0·43	3·85
	4	106·5	131	4·62	0·57	4·70
8	1	26·9	67	0·32	0·05	2·48
	2	53·8	104	1·25	0·16	3·00
	3	77·7	111	3·13	0·40	3·60
	3½	94·6	117	5·01	0·65	4·01
	4	106·4	124	5·84	0·76	4·80
9	1	23·4	64	0·26	0·04	2·78
	2	54·8	91	1·45	0·21	3·20
	3	81·5	115	3·93	0·56	4·19
	3½	92·7	120	5·09	0·73	4·86
	4	106·6	128	6·95	0·99	6·17
10	1	27·5	64	0·34	0·06	2·94
	2	53·2	81	2·03	0·35	3·72
	3	81·6	101	4·16	0·72	4·75
	3½	92·2	110	5·18	0·90	5·30
	4	105·0	114	6·51	1·14	6·11
11	1	28·4	63	0·31	0·04	2·38
	2	53·7	85	1·41	0·19	3·03
	3	80·0	107	3·32	0·46	3·48
	3½	91·7	116	4·45	0·62	4·41
	4	107·8	124	6·39	0·89	5·09
12	1	27·6	59	0·49	0·07	3·28
	2	54·6	86	1·45	0·21	3·73
	3	81·3	112	4·06	0·59	4·32
	4	109·6	120	7·14	1·03	6·31

Whittingham (1952) for 200 R.A.F. personnel (Table 6 (*a*)). The relationship for leg length is similar to that which can be calculated for the data of Booyens and Keatinge (1957) (Table 6 (*b*)).

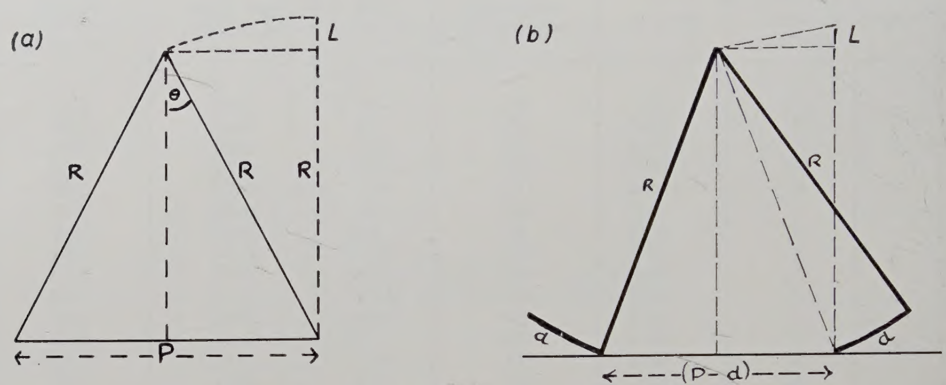

Figure 1. Simplified walking diagrams. For details see text.

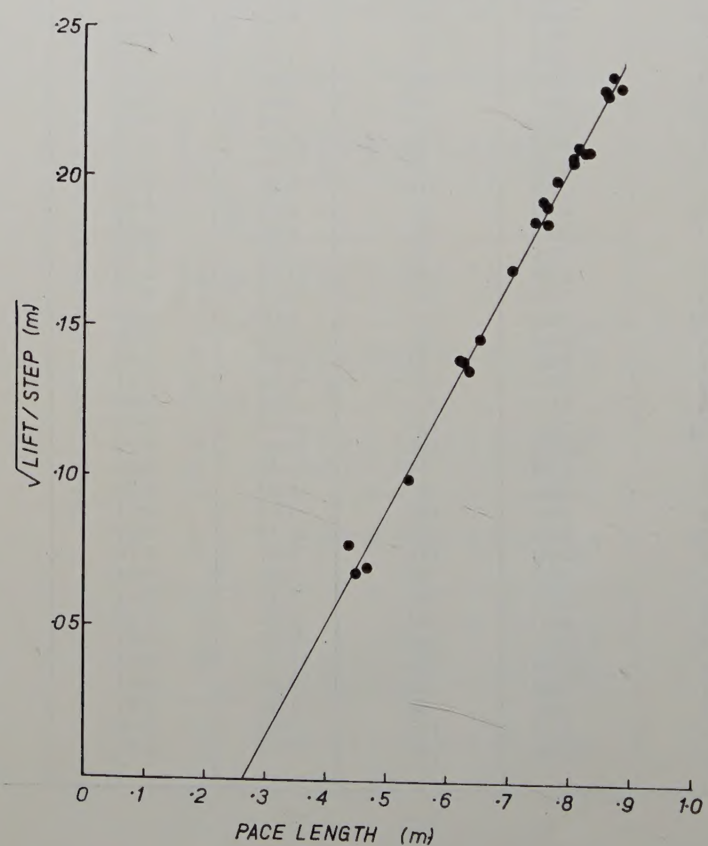

Figure 2. Relationship between square root of lift per step and pace length for subject walking naturally on the flat at 1–4 m.p.h. Regression line is calculated from eqn. (4).

3.2. *Mechanical Relationships in Walking on the Flat*

The amplitude of the vertical oscillation of the trunk (lift/step)

Measurements of lift per step agree well with those to be anticipated from a simple geometrical model which assumes that the knee joints are fully extended when the legs are in the astride position (cf. Elftman 1954). The simplest form of this model is a triangle, the sides of which are equal to the leg length (R) and the base is the pace length (P) (see Fig. 1 (a)). The difference (L) between the length R and the length of the perpendicular from the vertex to the base is then a measure of the fall of the trunk from the standing to the astride position. The maximum angle between the legs is sufficiently small for the following relationship to hold

$$L = P^2/8R \qquad (1)$$

i.e.

$$\sqrt{L} = P/\sqrt{(8R)}. \qquad (2)$$

On this model, therefore, we expect the square root of the fall (or rise) of the trunk *per step* to be linearly related to the pace length. This turns out to be the case; however, the regression lines do not pass through the origin but intercept the axis of pace length at values which approximate to the measured foot length (d). The remarkably good agreement with our data is illustrated for subject 2 in Fig. 2.

In the ten subjects, the value for the intercept averaged 88 per cent of the measured foot length (range 68 per cent to 123 per cent. This suggests to us

Table 3. Walking speed, step frequency, lift per minute and energy expenditure for subject 2 walking naturally on the flat

Walking speed (m/min)	Frequency (steps/min)	Lift (m/min)	Energy expenditure (kcal/min)
25·9	55	0·27	2·66
25·9	59	0·35	2·71
26·6	59	0·27	2·47
37·5	70	0·69	2·92
52·6	84	1·63	3·24
53·2	83	1·53	3·22
53·4	85	1·63	3·42
57·5	88	1·87	3·32
68·9	97	2·77	3·62
78·1	104	3·58	4·01
80·1	104	3·56	4·19
80·1	104	3·76	4·15
80·1	105	3·88	3·90
84·9	108	4·28	4·51
90·6	111	4·78	4·79
92·7	114	4·88	5·01
92·7	114	4·79	5·32
94·4	113	4·90	5·21
94·8	114	4·97	4·79
96·0	117	5·19	4·52
97·0	112	5·90	4·84
105·4	118	6·25	5·84
105·4	120	6·57	6·05
106·0	122	6·33	5·68

that, from the point of view of vertical lift per step, the effective pace length, when both feet are on the ground, is the distance between heel and toe, which in subsequent calculations we have assumed to be equal to $(P–d)$. This concept is illustrated in Fig. 1 (b).

Thus eqns. (1) and (2) can be amended as follows

$$L=(P-d)^2/8R, \qquad (3)$$

$$\sqrt{L}=(P-d)/\sqrt{(8R)}. \qquad (4)$$

Total vertical lift per minute

If we multiply both sides of eqn. (3) by the step frequency (n), simultaneously substituting $P=v/n$, where v is the walking velocity, we have

$$L_n=n\left(\frac{v}{n}-d\right)^2/(8R). \qquad (5)$$

This equation enables us to calculate total vertical lift per minute given the velocity of walking, the step frequency and the leg and foot lengths ($r=0{\cdot}97$; Table 6 (c)).

Total vertical lift and velocity

In addition to the relationships so far considered there is a linear relationship between the total vertical lift of the trunk per minute and the square of the walking velocity. This relationship holds for each subject ($r \geqslant 0{\cdot}97$) but the regression coefficients and constants vary from man to man. The constant term is small, however, when the data are combined (Table 6 (d)) so that, on average, the vertical lift of the trunk is proportional to the square of the walking velocity. If eqn. (5) is rearranged, taking this into account,

$$L_n=\frac{v^2}{8R}n\left(\frac{1}{n}-\frac{d}{v}\right)^2, \qquad (6)$$

it is clear that L_n can be proportional to v^2 only if

$$n\left(\frac{1}{n}-\frac{d}{v}\right)^2 \text{ is constant.}$$

Substitution of observed values shows that this is in fact so for walking speeds of 2 to 4 m.p.h.

Step frequency when walking naturally on the flat

It is likely that step frequency and walking speed are functionally related when walking naturally on the flat, but we have been unable to find any mathematical function that can describe the observed relationship (shown in Fig. 3) in terms of the physical or physiological attributes of the subjects.

A number of adequate, but empirical, relationships have been found, all of which yield correlation coefficients of not less than 0·97.

The constant, bracketed term of eqn. (6) is obviously one of them and is deduceable from two others having the form

$$v=pn^2+q, \qquad (7)$$

$$v=c\left[\frac{n-b}{1-an}\right] \qquad (8)$$

when the values of the constants are those obtained by the empirical fitting of our data to these expressions.

Table 4. Velocity (v) (m/min), step frequency (n) (per minute), lift (L) (m/min), and energy expenditure (E_{O_2}) (kcal/min), for subjects 2 and 12 walking up an inclined treadmill

		Subject 2			Subject 12											
Gradient percentage		4	8	12	4				8				12			
Walking speed (approx.)																
1 m.p.h.	v	25·3	26·7	26·7	27·0	27·5	28·0	27·4	26·9	28·2	27·4	28·0	26·6	25·8	28·0	27·7
	n	53	58	60	56	62	58	57	56	59	54	54	61	60	62	61
	L	0·40	1·01	1·33	0·35	0·46	0·29	0·44	0·43	0·56	0·56	0·48	0·77	0·62	0·72	0·67
	E_{O_2}	3·15	3·65	4·33	3·74	3·38	3·92	3·53	4·15	3·92	3·97	4·12	4·27	4·60	4·66	4·44
2 m.p.h.	v	53·0	54·2	54·8	53·6	55·4	54·8	52·9	54·3	52·7	54·3	52·9	54·1	54·3	53·6	53·4
	n	79	82	86	91	90	86	89	91	83	95	85	94	94	94	87
	L	1·88	2·91	3·64	1·46	1·03	1·17	1·01	1·68	1·07	2·14	1·08	2·35	1·48	2·35	1·82
	E_{O_2}	4·36	5·36	7·13	4·98	4·60	4·73	4·49	5·18	5·38	5·43	5·28	6·33	6·82	6·49	6·93
3 m.p.h.	v	80·1	81·6	80·1	80·7	76·3	81·3	81·3	81·3	78·3	79·7	81·3	80·7	81·3	81·3	81·0
	n	102	105	102	108	111	111	107	111	111	108	106	105	113	110	114
	L	4·17	5·22	5·94	4·56	3·66	4·08	4·01	4·85	4·39	4·79	4·61	5·37	5·21	6·39	5·39
	E_{O_2}	5·89	7·47	9·58	5·73	5·87	6·05	5·83	7·12	7·10	7·05	7·24	9·23	9·59	9·20	8·99
4 m.p.h.	v	106·9	107·5	107·8	107·2	109·6	115·5	108·6	107·7	109·6	109·6	108·7	108·5	105·0	109·6	109·6
	n	119	120	121	119	128	115	124	121	118	126	125	123	125	122	120
	L	8·97	7·31	8·32	7·90	7·02	7·13	6·84	9·19	7·44	7·94	7·94	10·39	9·19	8·77	8·82
	E_{O_2}	8·34	9·88	12·11	7·74	8·03	8·31	8·15	10·28	9·65	9·55	9·89	11·01	12·00	11·09	11·13

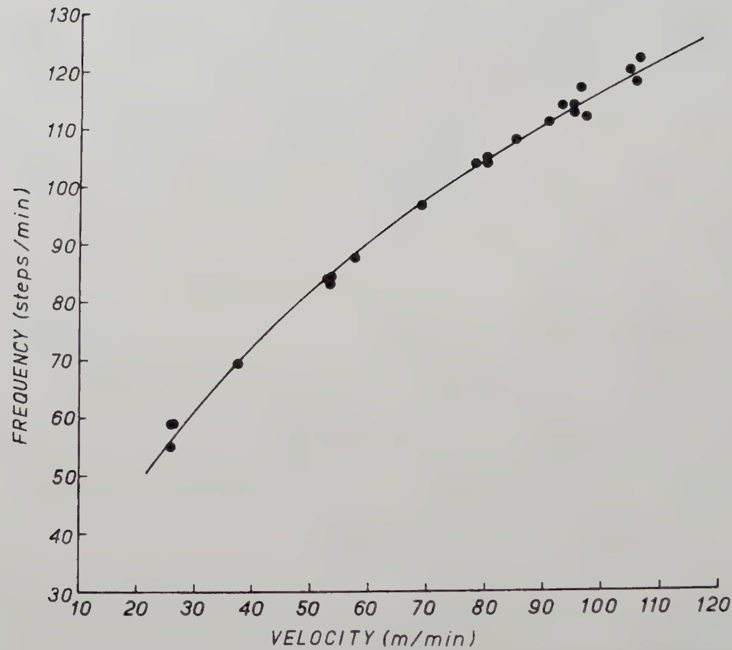

Figure 3. Relationship between velocity and spontaneously chosen step frequency for subject 2 walking naturally on the flat.

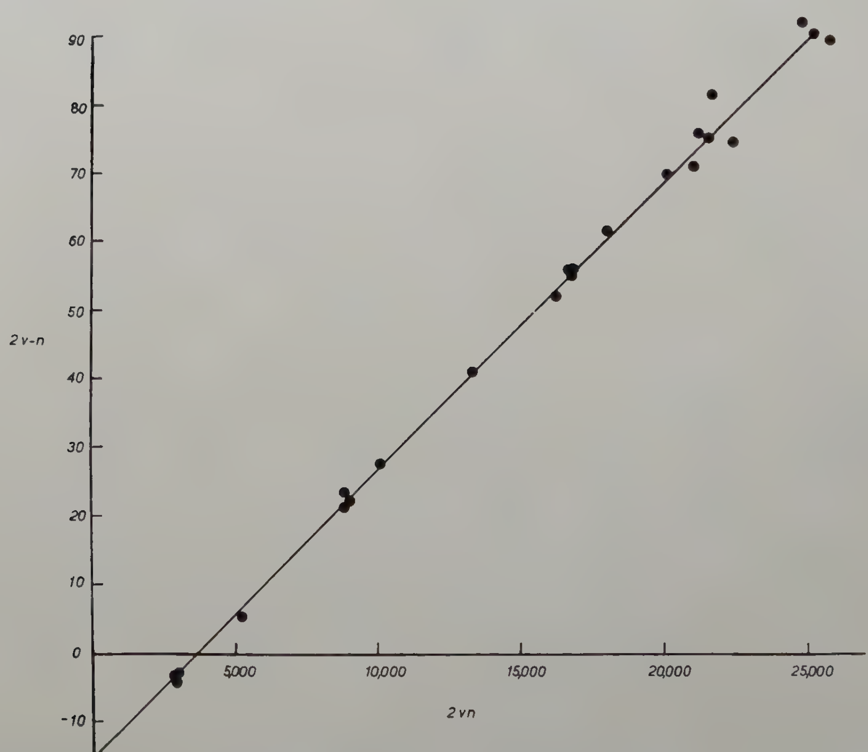

Figure 4. Relationship of twice the velocity minus the frequency with the product of velocity and frequency for subject 2 walking naturally on the flat at 1–4 m.p.h.

Equation (8), which resembles the hyperbolic relationship of Scholz (1953), gives the most exact fit of any of the relationships investigated. Rearranged in a manner suitable for a linear regression it is illustrated for data on subject 2 in Fig. 4. On purely empirical grounds c was assumed to be 0·5, giving a regression of $(2v-n)$ on $2vn$. The constants of these equations vary too much from man to man to permit satisfactory prediction of natural step frequency at a given walking velocity.

3.3. *Oxygen Consumption when Walking Naturally on the Flat*

The rate of metabolic energy expenditure (E_{O_2}) is linearly related to the rate of doing lift work (W_L) and to the square of the walking velocity (v^2) (Table 6 (e) and (f)).

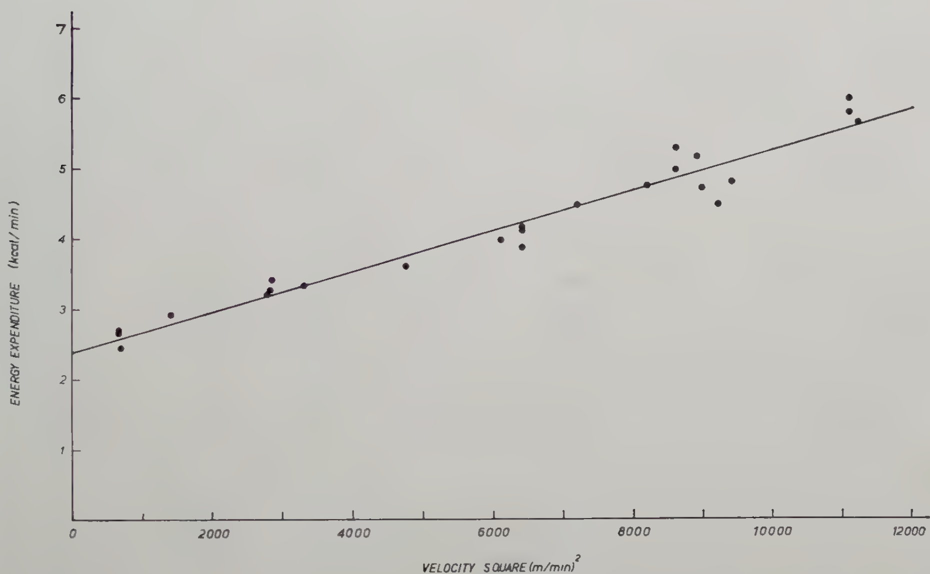

Figure 5. Regression of energy expenditure on velocity squared for subject 2 walking naturally on the flat at 1–4 m.p.h.

The regression coefficients and constants of the equations vary from subject to subject and are to some extent related to body size (Table 6 (g) and (h)). The relationships for subject 2 are illustrated in Fig. 5 and and by the open circles in Fig. 6, and the regression of E_{O_2} on W_L for the pooled data in Fig. 7. This relationship can be used to predict energy expenditure from lift work to within 0·7 kcal over the range 2·4–6·1 kcal in 95 per cent of cases.

The constants of these equations, giving the metabolic energy expenditure at zero work level or velocity, are considerably in excess of the observed E_{O_2} standing still. Thus, if these linear extrapolations are justified, there is an energy cost of walking which is independent of walking velocity or work level.

The mechanical efficiency of walking

This may be defined as the ratio of the rate at which the muscles are doing mechanical work to the rate of metabolic energy expenditure (E_{O_2}). We have

Table 5. Lift work and energy expenditure of walking down an inclined treadmill

Subject	Gradient (per cent)	Walking speed (m.p.h. approx.)	Walking speed (m/min)	Frequency (steps/min)	Lift (m/min)	Energy expenditure (kcal/min)	Lift work (kcal/min)
1	8	1	24·9	61	0·84	2·53	0·13
		2	53·7	75	2·68	2·53	0·42
		3	77·2	111	4·59	3·06	0·71
		4	105·0	120	6·49	4·29	1·01
2	2	1	25·3	58	0·42	2·36	0·07
		2	54·8	88	2·05	2·82	0·33
		3	78·6	105	4·05	3·40	0·65
		4	103·5	121	6·39	4·62	1·02
	4	1	26·2	61	0·25	2·28	0·04
		2	50·6	85	1·44	2·70	0·23
		3	78·4	107	3·37	3·41	0·54
		4	106·3	123	6·06	4·70	0·97
	4	1	24·2	60	0·30	2·18	0·05
		2	52·2	89	1·69	2·66	0·27
		3	75·9	105	3·70	3·23	0·59
		4	102·4	121	6·20	4·44	0·99
	8	1	25·9	66	0·44	2·23	0·07
		2	52·6	94	1·94	2·66	0·31
		3	79·2	107	4·48	3·05	0·72
		4	106·8	125	7·24	4·40	1·16
	12	1	25·3	67	0·56	2·19	0·09
		2	52·8	97	2·41	2·65	0·39
		3	77·6	113	4·66	3·22	0·75
		4	105·4	124	7·81	4·24	1·25
4	8	1	28·0	60	0·63	2·16	0·09
		2	54·8	89	1·93	2·37	0·27
		3	81·1	107	4·54	3·13	0·62
		4	108·2	130	7·95	3·90	1·09
5	8	1	27·7	66	0·52	2·14	0·08
		2	55·6	92	2·16	2·42	0·33
		3	80·1	111	4·10	3·13	0·62
		4	105·4	122	7·57	4·08	1·14
6	8	1	27·1	57	0·63	1·62	0·08
		2	54·8	85	2·46	1·95	0·31
		3	79·5	104	5·41	2·47	0·69
		4	104·4	128	7·21	3·28	0·92
7	8	1	27·5	81	0·39	1·73	0·05
		2	56·8	104	1·40	1·96	0·18
		3	78·9	117	3·78	2·46	0·47
		4	104·4	133	6·15	3·13	0·76
8	8	1	26·5	78	0·59	2·14	0·08
		2	51·4	98	1·69	2·25	0·22
		3	78·1	111	4·29	2·46	0·56
		4	105·4	128	7·63	3·46	0·99
9	8	1	24·3		0·40	2·11	0·06
		2	53·4	94	1·96	2·31	0·28
		3	80·1	116	5·26	2·78	0·75
		4	107·2	133	7·77	4·27	1·11
10	8	1	22·2	64	0·47	2·54	0·08
		2	52·5	83	2·12	2·97	0·37
		3	77·8	102	4·51	3·32	0·79
		4	103·2	116	7·51	4·30	1·31
11	8	1	25·0	71	0·45	1·74	0·06
		2	53·7	88	2·11	2·17	0·29
		3	77·1	110	4·97	2·42	0·69
		4	105·4	124	8·90	3·38	1·23

estimated the work done against gravity by measuring the vertical oscillation of the trunk in walking. More properly, we should have measured the vertical movement of the centre of gravity of the body. Measurements of this movement (see § 2 and Table 1) suggest that it is about 9/10 of the vertical movement of the trunk per step. Our 'lift work' is therefore proportionately overestimated. But in addition to the vertical oscillation, there are also horizontal oscillations of the body in the direction of walking and at right angles to it. We have made crude measurements of the amplitude of the oscillations of the trunk in the direction of walking and, assuming as a first approximation that the motion is simple harmonic, we calculate that the change in kinetic energy per step approximates to the work of lift per step.

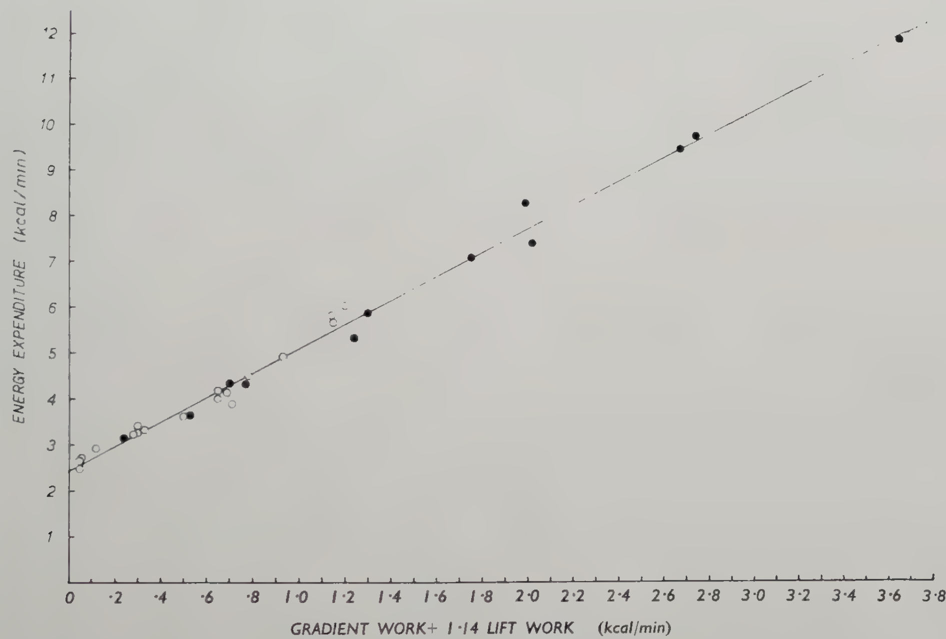

Figure 6. Regression of energy expenditure on lift and gradient work per minute for subject 2 walking naturally on the flat (open circles) and up gradients of 4, 8 and 12 per cent (closed circles) at 1–4 m.p.h.

These movements of the body, in walking, were studied in detail by Fischer and, although we have been unable to integrate his analysis to obtain an estimate of the total mechanical work output, we are clearly warned that the work of vertical oscillation may not, by itself, be used to compute the efficiency of walking.

There are, however, two circumstances in which the vertical work must be proportional to the total mechanical work done. The first is when walking naturally on the flat, where we have shown that it is linearly related to the total metabolic energy expenditure. The second is when walking at different speeds but at a fixed step frequency. This will be discussed in § 3 subsection 3.3.4.

The most efficient walking velocity

The most efficient walking velocity can be defined as that at which the energy cost per unit of distance moved is at a minimum. This velocity was

experimentally determined by Magne (1920) and Atzler and Herbst (1927), with respect to energy expenditure in excess of the resting level

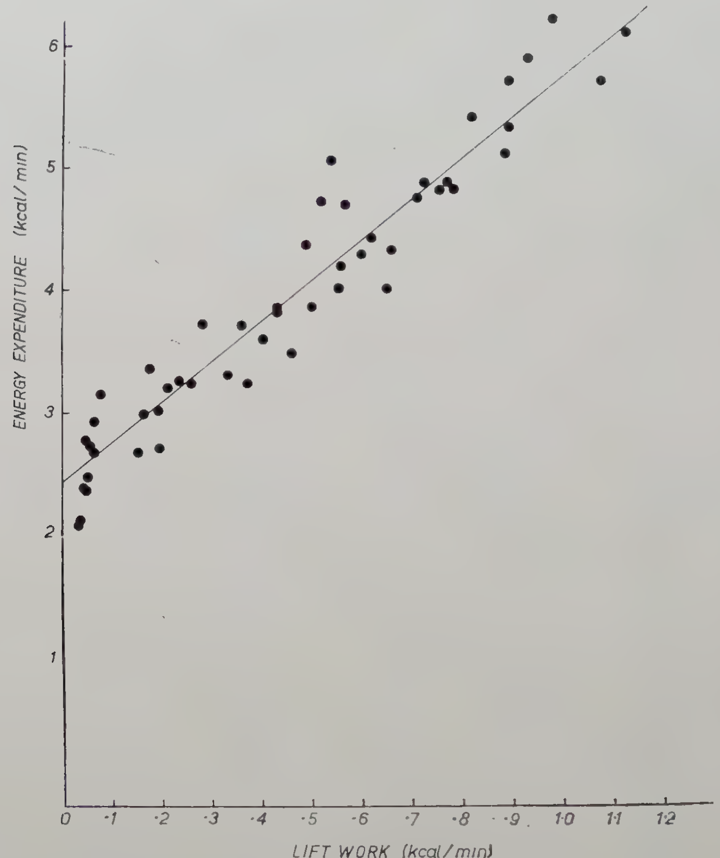

Figure 7. Regression of energy expenditure on lift work for 10 subjects walking naturally on the flat at 1–4 m.p.h.

It can also be deduced from the relationship which we have observed between E_{O_2} and v^2. This relationship may be written

$$E_{O_2} = av^2 + b \qquad (9)$$

where a and b are constants. On rearrangement after subtracting from both sides the resting energy expenditure per minute (r) we get

$$(E_{O_2} - r)/v = \frac{av^2 + (b-r)}{v} \qquad (10)$$

where $(E_{O_2} - r)/v$ is the energy cost per unit distance moved. This expression can be shown to have a minimal value when

$$v = \sqrt{\left(\frac{(b-r)}{a}\right)}. \qquad (11)$$

Substituting our mean values for a, b and r in eqn. (10) gives the optimal velocity as 60·2 m/min or $2\frac{1}{4}$ m.p.h., which is almost identical with the value determined in earlier investigations.

If the resting rate of energy expenditure is not excluded, the minimum occurs when

$$v = \sqrt{(b/a)} \quad \ldots \ldots \ldots \ldots \quad (12)$$

or substituting $v = \sqrt{(b/a)}$ in eqn. (9).

$$E_{O_2} = 2b, \quad \ldots \ldots \ldots \ldots \quad (13)$$

thus stating that at the most economic walking velocity the rate of metabolic energy expenditure is twice that obtained on extrapolation back to zero velocity—whatever this quantity may signify. From our subjects the corresponding velocity is 95·4 m/min or 3½ m.p.h. which also has experimental confirmation (Morton and Fuller 1952).

The relationship of energy expenditure and lift work rate at other than natural step frequency

(*a*) *Constant velocity and varying step frequency.* We have found that if a subject walks at a fixed velocity but varies his step frequency by alteration of pace length, there is no longer a linear relationship between energy expenditure and lift work rate (Fig. 8). Our observations are in agreement with Magne's

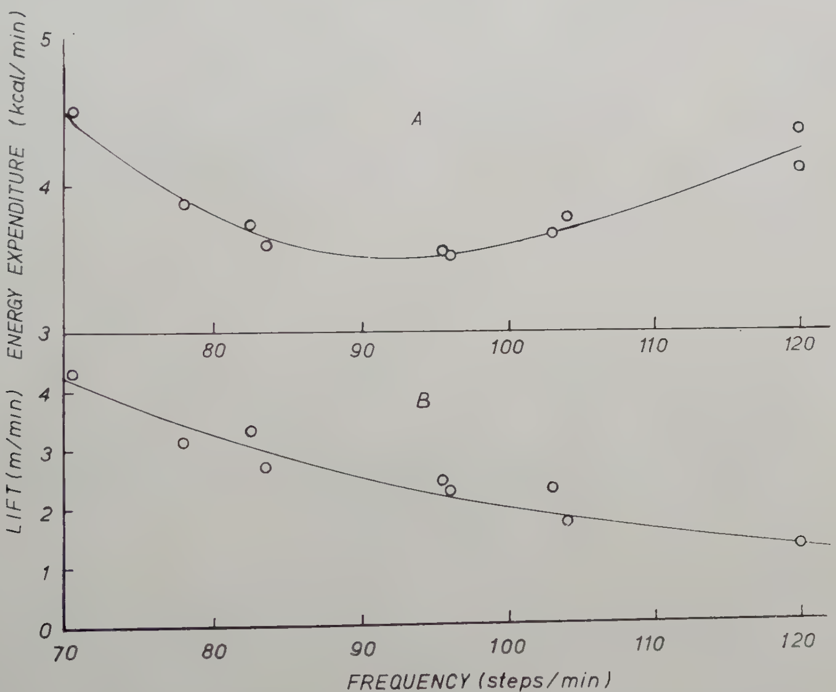

Figure 8. Relationship between step frequency per minute and (A) energy expenditure, (B) lift per minute for subject 2 walking at controlled step frequencies on the flat at approximately 2½ m.p.h. Continuous line (B) is calculated from eqn. (3).

finding (1920), that there is a step frequency at which energy expenditure is minimal. There is, however, no corresponding minimal rate of lift work as postulated by Benedict and Murschhauser (1915) for conditions of minimal energy expenditure. Both our observations (Fig. 8) and calculations from eqn. (5) show that the rate of lift work decreases continuously as the step frequency rises.

(*b*) *Constant step frequency, varying walking velocity.* Re-analysis of the data of Atzler and Herbst (1927) suggests to us that if a subject walks at a fixed frequency but varies his walking velocity by alteration of pace length, there is again a linear relationship between E_{O_2} and the rate of lift work. These authors measured, in one subject, the energy expenditure in excess of resting, of walking at step frequencies of 50, 75, 100, 130 and 150/min and at pace lengths of 45, 60, 75 and 90 cm in all combinations. Lift work was not recorded, but as the weight of the subject and the relationship between his walking velocity and natural step frequency were in close agreement with the mean values for our ten subjects, we felt justified in using their mean leg and foot lengths in its calculation. We then found at each step frequency a linear relationship between energy expenditure and calculated lift work. The constants of the regressions, representing energy expenditure at zero lift work increase continuously from 0·8 kcals at 50 paces/min to 3 kcals at 150 paces/min. The coefficients of the regressions, which are the ratios of corresponding increments of energy expenditure and lift work rate have a minimum value of about 3 at 105 steps/min.

We have developed an expression which describes, with considerable accuracy for this subject, the energy expenditure at combinations of pace length and step frequencies of 75/min and above (Table 6 (*i*)). The relationship is in the form

$$E_{O_2} = \frac{n}{n-50}\left[\frac{1-b/n}{1-an}\right] W_L + \left[\frac{1-b/n}{1-an}\right]\sqrt{\left(\frac{n}{100}\right)} + r \quad . \quad . \quad (14)$$

where r is the resting energy expenditure, n the step frequency and b and a the constants of eqn. (8).

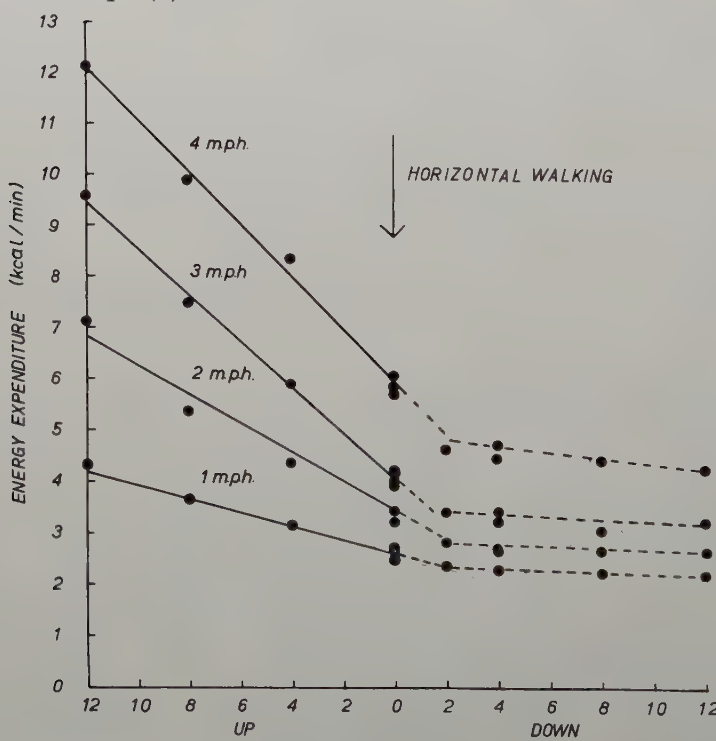

Figure 9. Relationship between energy expenditure and percentage gradient for subject 2 walking naturally on the flat and up and down inclines of 2–12 per cent at 1–4 m.p.h.

Applied to the data of subject 2 the energy expenditures calculated using this expression are linearly related ($r = 0{\cdot}98$) to the observed E_{O_2} when walking naturally on the flat. The expression may therefore represent an approach to a more general relationship between the work of vertical oscillation and total energy expenditure in walking.

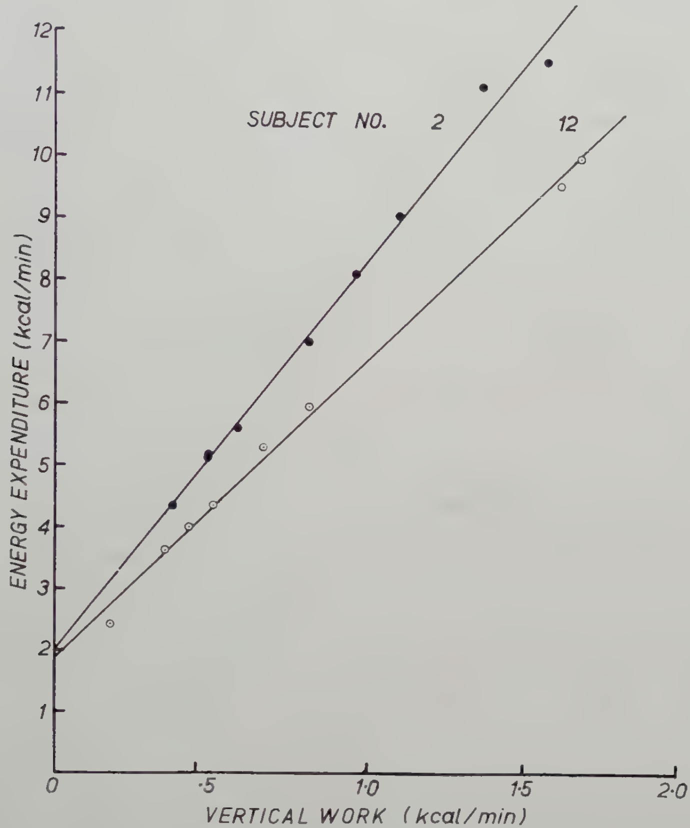

Figure 10. Regressions of energy expenditure on vertical work for subjects 2 and 12 performing stepping exercise.

3.4. *Incline Walking*

Uphill

The energy equivalent of the gradient work done by the subject per minute in walking uphill can be calculated by subtracting from the total energy expenditure (Table 4) that attributable to walking at the same speed on the flat (Table 6 (*f*)) (cf. Smith 1922, Erickson *et al.* 1946). When this is done a linear relationship between gradient work per minute and its energy equivalent is obtained ($r \geqslant 0{\cdot}98$) (Table 6 (*j*)). Since the regression coefficients and those of E_{O_2} on W_L on the flat are very similar (Tables 6 (*j*) and (*e*)) the energy expenditure of uphill walking can be described in terms of the sum of these two components. It can also be described with equal precision using the observed lift work up the incline and regression relationship for subjects 2 and 12 and E.D.B. (Smith 1922) have been reported (Cotes, Meade and Wise, 1957) (Table 6 (*k*)). Such relationships (e.g. Fig. 6) may have a use in the prediction of

energy expenditure but could be misleading as lift work so measured may include a component which is related directly to the incline of the treadmill.

Downhill

Data obtained for downhill walking (Table 5) were analysed in terms of velocity, lift and gradient work. For all subjects at an 8 per cent gradient the

Table 6. Regression relationships referred to individually in the text

Relationships	Subjects	Other sources	Regression Coefficient	Regression Constant	Correlation coefficient
(*a*) Foot length on height	1–12	A	0·128	+0·040	0·70
	200 R.A.F.		0·124	+0·049	0·69
(*b*) Leg length on height	1–12	B	0·602	−12·8	0·92
	10 women		0·703	−29·3	0·93
	10 men		0·728	−34·8	0·97
	combined		0·638	−18·9	0·97
(*c*) Observed on calculated lift work	1–11		0·98	+0·028	0·97
(*d*) Lift work on v^2	1–11		0·000531	−0·0227	0·97
(*e*) Energy expenditure of horizontal walking on lift work	1–11		3·25	+2·40	0·98
	2		3·05	+2·44	0·99
	12	C	2·99	+2·99	0·95
	M.A.M.		3·35	+2·15	0·91
(*f*) Energy expenditure of horizontal walking on v^2	1–11		0·000260	+2·38	0·98
(*g*) Coefficient of regression of E_{O_2} on W_L on					
(i) Body weight	1–12		−0·054	+6·68	−0·61
(ii) Leg length			−8·61	+11·2	−0·67
(iii) Body surface area			−0·349	+3·99	−0·70
(*h*) Constant of regression of E_{O_2} on W_L on					
(i) Body weight	1–12		0·034	+0·35	0·67
(ii) Leg length			6·19	−3·17	0·82
(iii) Body surface area		D	2·39	−1·62	0·80
(*i*) Observed on calculated energy expenditure of walking			1·01	−0·025	0·99
(*j*) Gradient energy expenditure on gradient work	2		3·1	+0·15	0·99
	12		2·86	−0·009	0·98
(*k*) Energy expenditure of uphill walking on lift and gradient work	2		3·06 and 2·68	+2·40	0·99
	12		2·70 and 2·62	+3·08	—
		E	±0·049+0·113	±0·104	
(With standard errors)	E.D.B.		3·09 and 2·60	+1·78	
			±0·035+0·078	±0·089	—
(*l*) Energy expenditure of walking down 8 per cent incline on v^2	1–11		0·000169	+1·90	0·98
(*m*) Energy expenditure of stepping exercise on vertical work	2		6·3	+2·0	0·99
	12		4·83	+1·89	0·99
(*n*) Energy expenditure per kg body weight of horizontal walking on v^2	1–11		$4·25 \times 10^{-6}$	+0·0386	See text

A = Morant and Whittingham (1952) ; B = Booyens and Keatinge (1957) ; C = Benedict and Murschhauser (1915) ; D = Atzler and Herbst (1927) ; E = Smith (1922).

rate of energy expenditure was found to be proportional to velocity squared (Table 6 (l)): however, when the data were analysed in terms of lift and gradient work a curvilinear relationship was obtained. For the more complete data on subject 2, relationships developed for uphill walking also applied to walking down a 2 per cent gradient (Fig. 9): for steeper inclines no simple relationship between energy expenditure, lift and gradient work was obtained.

3.5. *Stepping Exercise*

The energy expenditure and vertical work done per minute in stepping exercise were measured in subjects 2 and 12 for comparison with the energy-lift work relationships obtained for normal walking. Linear relationships between lift work and energy expenditure were obtained (Table 6 (m)). These are illustrated in Fig. 10. The regression coefficients are 50–100 per cent greater than those obtained for the energy expenditure of walking on lift or gradient work (Table 6 (m) and (e)). Thus vertical work apparently accounts for a smaller proportion of the total energy expenditure of stepping on and off a box than it does of normal walking.

§ 4. Discussion

In 1951, A. V. Hill wrote that " Progress of knowledge is achieved by trial and error, by experiment and theory acting and reacting on one another. The vital thing is that the error should be confined to the theory and should not be allowed by carelessness or credulity to creep into the experiments."

In the preparation of this analysis, there was undoubtedly much reacting between experiment and theory and perhaps overmuch credulity in our persistent efforts to find simple relationships in this complex field of study. We hope, however, that in our observations there are only the quantitative errors of imperfect instrumentation. In this we are fortified by the general agreement between our findings and the observations of other workers.

We have re-examined the data of Benedict and Murschhauser (1915) and Smith (1922), who made numerous measurements of lift per step, pace length and energy expenditure on two subjects, M.A.M. and E.D.B., and find that their observations conform to the relationships which we have described, although less perfectly than our own data. Benedict and his co-workers were unaware of the relationship of energy expenditure with lift work which is apparent in their data for M.A.M. at 2–4 m.p.h. on the flat (Table 6 (e)) and E.D.B. performing level and grade walking (Table 6 (k)). This oversight is perhaps attributable to their observation that the lift work performed by M.A.M. whilst *trotting* at $5\frac{1}{4}$ m.p.h. on the horizontal treadmill was greater than that for 'walking' at the same speed whereas the energy expenditure was less. From this they concluded that lift work and energy expenditure are not interrelated. Had they confined their observations to normal walking they might have interpreted their findings differently.

In experiments done on an individual over a period, a number of factors could contribute to such scatter as is apparent in the data of these authors. Among these may be changes in walking mannerisms, associated either with the state of relaxation on a particular occasion or increasing familiarity with walking on a treadmill. The comparability of experiments, identical with

respect to walking speed, may also be affected by the amount of arm swinging, if this is permitted, or by the subject, surreptitiously or otherwise, gaining support by resting an arm on any guide rail that may be built on to the treadmill.

The phrase 'walking mannerisms' covers not only the problem of the repeatability of experiments on an individual but also those differences between individuals which we have been unable to resolve in terms of the physical and physiological variables which we have investigated.

It is not difficult to see that the cyclical accelerations of walking, both vertical and horizontal, will require compensatory changes in muscular tensions throughout the body, if balance and posture is to be maintained.

The energy requirements of these processes will depend on the absolute magnitude of the tensions and changes of tensions involved and also on the frequency of the changes. This in turn will be related to the mechanical and dimensional characteristics of the subject.

In addition, when walking naturally the sequence of operations appears to be governed by the principle of minimal energy expenditure at a chosen velocity, upon which may be superimposed the purpose, preference and habits of the subject.

If walking involves activity of muscles throughout the body, then the physical fitness of a subject and his muscular development, both general and topical will affect his performance.

We have investigated, on ten subjects, the effect of physical training on the relationship between energy expenditure and work of lift (Cotes and Meade 1959). At intervals over a period of physical training, these subjects walked on a horizontal treadmill at $3\frac{1}{2}$ m.p.h. We found that the relationship between energy expenditure and work of lift remained unaltered throughout this period, but that the subjects had contrived to walk at the fixed speed with diminishing vertical oscillation and consequently with decreasing total energy expenditure. It is possible that both the physical training and increasing familiarity with walking on a treadmill contributed to these results. Such changes may be equivalent to changes in effective leg length, associated with subjective reassessment of maximal comfort in walking, but such an explanation is not helpful either in understanding the reasons for the changes, or for predicting their magnitude.

The problem of *predicting* energy expenditure in walking from basic mechanical and physiological principles remains unsolved. But in the related problem of interpolation, i.e. the 'calibration' of an individual for treadmill walking, we have been more successful. We have found that, for any individual, energy expenditure is highly correlated with both work of lift and the square of the walking velocity over a range from 1–4 m.p.h., the linear equations derived permitting convenient and accurate interpolation.

However, the unresolved differences between individuals are not so great as to preclude the development of prediction formuli of limited accuracy and for this purpose the most convenient relationship is that between energy expenditure and the square of the walking velocity. For the data from our group of ten subjects as a whole, a linear regression of energy expenditure per kilogram body weight on the square of the walking velocity gives an equation (Table 6 (n)) which, in 95 per cent of cases, can predict the energy expenditure

of members of this group to within 0·7 kcals/min over the range 1–4 m.p.h. From this equation, which describes a parabolic relationship between energy expenditure and walking velocity, a number of approximate, linear functions could be deduced which would hold over a limited range of velocities. Such a linear function was proposed by Passmore and Durnin (1955) but, as applied to our data, it shows systematic errors at 2 and 4 m.p.h., as indeed must inevitably follow from the high correlation we have found for the more comprehensive relationship.

We consider that step frequency plays a fundamental role in the ergonomics of walking and have found a number of empirical relationships between natural step frequency and walking velocity. However we have been unable to account for the variations from man to man possibly because factors such as pelvic shape and the limitations imposed by the ileo femoral ligaments on the excursion of the hip joint (Booyens and Keatinge 1957) or on the period of free oscillation of the leg (e.g. Hettinger and Muller 1953) are not correlated with the indices we used. The fundamental nature of step frequency is emphasized in our analysis of the data of Atzler and Herbst. In this we found that, when walking at a constant step frequency, metabolic energy expenditure and lift work are linearly related; by contrast when walking at a constant velocity with varying step frequency there is no longer a linear relationship between energy expenditure and work of lift, although there is a particular step frequency at which energy expenditure is minimal at a given walking velocity.

Step frequency is a measure of the frequency and speed of contraction of the muscles involved in propulsion and equilibrium in walking and the analysis therefore suggests that the proportionality between energy expenditure and rate of working may be a function of the frequency or speed of muscle contraction.

The constants of proportionality are likely to be influenced in part by the bodily configuration which is an individual characteristic: to this we ascribe variations in energy expenditure between one individual and another.

The present analysis has demonstrated some of the factors underlying the finding by Brockett and his co-workers (1956) that leg length and energy expenditure of walking are inversely related. It is hoped that future work will demonstrate how other individual characteristics also affect the pattern of energy expenditure observed in walking and how this is related to the dynamics of isolated muscle.

We are indebted to the Army Personnel Research Committee and to our subjects for their co-operation in this investigation: to Miss C. Yandle and other members of the Unit staff for most valuable assistance: to Mr. P. D. Oldham and Dr. M. E. Wise for help with the statistical analyses of the data and to Dr. J. C. Gilson (Director, Pneumoconiosis Research Unit) for advice and helpful criticism both during the study and in the preparation of this paper.

La dépense énergétique, le travail d'élévation verticale du tronc à chaque pas et les longueurs de jambe et de pieds ont été mesurés chez 11 sujets jeunes de sexe masculin, marchant sur un tapis roulant horizontal à des vitesses de 1,6 à 6,4 km/h à cadence normale de marche. Dans certains cas, ces déterminations ont été faites lorsque la marche était effectuée à cadence imposée ou bien lorsque le tapis roulant était incliné dans le sens d'une montée ou d'une descente. Des déterminations similaires ont été faites lors de l'ascension d'un escabeau. Ces résultats et ceux de la bibliographie ont été analysés.

L'élévation verticale par pas (L) est une fonction géométrique des longueurs de la jambe, du pied et du pas (respectivement R, d et P) telle que

$$L=(P-d)^2/8R$$

La dépense énergétique de la marche à cadence normale sur tapis roulant horizontal est une fonction linéaire du travail d'élévation verticale qui est le produit : (élévation verticale par pas) × (cadence de marche) × (poids du corps).

Cette relation n'est plus valide pour des cadences de marche arbitraires supérieures ou inférieures à celles adoptées spontanément. Dans ces conditions, la dépense énergétique de la marche à une vitesse donnée, augmente : au contraire, l'élévation et le travail d'élévation verticale décroissent progressivement à mesure que la cadence de marche s'élève, conformément à la relation géométrique ci-dessus.

Néanmoins, il a été établi une relation selon laquelle la dépense énergétique redevient une fonction linéaire du travail d'élévation verticale, à condition de tenir compte de la cadence de marche.

La dépense énergétique de la marche en montée (mais non en descente) à cadence de marche naturelle peut être décrite dans les mêmes termes, compte tenu du travail additionnel d'élévation verticale. L'analyse de la dépense énergétique d'un exercice d'ascension d'escabeau suggère que, par rapport à la marche, une moindre fraction de l'énergie totale est dépensée en travail d'ascension verticale.

La dépense énergétique de la marche horizontale à cadence de marche normale est une fonction linéaire du carré de la vitesse d'avancement horizontal. Cette relation à été appliquée au calcul de la dépense énergétique minima par unité de longueur de déplacement horizontal.

Les vitesses ainsi obtenues sont respectivement de 5,6 ou 3,6 km/h selon que l'on inclut ou exclut la dépense énergétique de repos, valeurs en accord avec celles déterminées expérimentalement. L'extrapolation linéaire de l'équation de régression donne une dépense énergétique à vitesse nulle de 2,4 kcal/min en surplus de la dépense de repos effectivement observée.

La prédiction de la dépense énergétique de la marche (E_{0_2}) peut se faire soit à partir du travail d'élévation, soit à partir de la vitesse. L'utilisation de la première relation exige la connaissance des longueurs de la jambe, des pieds et du pas que le sujet adoptera à une vitesse donnée ; ce dernier ne s'avère pas jusqu'ici susceptible d'être prévu. La seconde relation est de la forme :

$$E_{0_2}/W=0{,}0386\times 4{,}25\times 10^{-6}v^2 \text{ kcal/kg/min}$$

et peut servir à la prédiction de la dépense énergétique de la marche chez nos sujets avec une approximation de 0,7 kcal dans 95 p. 100 des cas. Une plus grande précision peut être atteinte par une calibration individuelle des sujets.

Der Energieaufwand, der vertikale Hub des Körperstammes je Schritt und die Bein- und Fusslängen wurden an 11 jungen männlichen Personen gemessen, die auf einer horizontalen Tretbahn mit 1·6 . . . . 6·4 km/h und natürlicher Schrittfrequenz gingen. In einigen Fällen waren die Schrittfrequenzen vorgegeben. Einige Versuche betrafen das Gehan bergauf und bergab. Aehnliche Messungen wurden beim Steigen auf bzw. von einer Kiste unternommen. Diese Messungen und andere aus der Literatur wurden analysiert.

Der vertikale Hub je Schritt (L) ist eine geometrische Funktion der Längen von Bein (R), Fuss (d) und Schritt (P) derart, dass $L=(P-d)^2/8R$.

Der Energieaufwand beim Gehen mit natürlicher Schrittfrequenz auf der horizontalen Tretbahn steht in linearer Beziehung zur vertikalen Hubarbeit, die das Produkt aus Hub/Schritt, Schrittfrequenz und Körpergewicht ist.

Diese Beziehung gilt nicht für vorgegebene Schrittfrequenzen, die über oder unter den willkürlich gewählten liegen. Unter diesen Bedingungen wächst der Energieaufwand für das Gehen für eine bestimmte Zunahme der Geh-Geschwindigkeit ; im Gegensatz dazu nehmen der Hub und die Hubarbeit progressiv mit grösserer Schrittfrequenz entspreshend dem geometrischen Verhältnissen ab. Trotzdem scheint unter Berücksichtigung der Schrittfrequenz der Energieaufwand wieder eine lineare Beziehung zur Hubarbeit einzuhalten.

Der Energieaufwand für das Aufwärtsgehen mit natürlicher Schrittfrequenz kann in ähnlichen Gleichungen dargestellt werden, wenn die zusätzliche Hubarbeit durch Steigen in Rechnung gesetzt wird. Das gilt nicht für Abwärtsgehen. Eine Analyse der Arbeit des Kisten-auf-und-ab-Steigens macht wahrscheinlich, dass im Vergleich zum Gehen ein geringerer Teil des Gesamtumsatzes für vertikale Hubarbeit aufgewendet wird.

Der Energieaufwand des horizontalen Gehens mit natürlicher Schrittfrequenz steht in linearer Beziehung zum Quadrat der Geh-Geschwindigkeit. Diese Beziehung wurde benutzt, um die Geschwindigkeit des geringsten Energieaufwandes je m Weg zu berechnen.

Die so erhaltenen Geschwindigkeiten sind inclusive Grundumsatz 5·6 km/h, ohne Grundumsatz 3·6 km/h, Werte, die mit den experimentell erhaltenen übereinstimmen. Die lineare Extrapolation der Regressionslinie gibt einen mittleren Netto-Energieaufwand für die Geschwindigkeit 0 won 2·4 kcal/min.

Die Berechnung des Energieaufwandes für das Gehen wurde sowohl aus der Hubarbeit als auch aus der Geh-Geschwindigkeit versucht. Bei Benutzung der Hubarbeit als Ausgangsgrösse muss man Bein- und Fusslängen und die willkürliche Schrittzahl bei einer gegebenen Geh-Geschwindigkeit kennen. Die Benutzung der Geh-Geschwindigkeit als Ausgangsgrösse erwies sich nicht als geeignet für eine Berechnung. Eine Gleichung, die die Berechnung des Energieaufwandes in 95% der Fälle innerhalb 0·7 kcal erlaubt, wird angegeben.

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THE ELECTROMYOGRAPHY OF FATIGUE

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The changes in the electrical activity of muscle during and following fatigue are discussed.

There are changes in size and form of the action potential ; synchronization occurs in the motor unit discharges.

In fatigue which follows a short strong contraction, the electrical changes can be shown to depend on peripheral factors, mainly the failure of the contractile mechanism to produce as much tension as in the normal state. Thus, as the contraction proceeds, the integrated electrical activity in a muscle exerting a constant tension increases gradually. When the contraction ceases, the electrical activity falls rapidly to its unfatigued level, as measured by brief test contractions of the same force. An arterial occluding cuff prevents this recovery, if inflated at the end of the contraction.

Muscular tremor, as recorded both mechanically and by the grouping of action potentials, is increased during and after muscular fatigue.

§ 1. Introduction

The continued contraction of muscle is associated with a sequence of physiological events which may conveniently be termed muscular fatigue. If a contraction is made voluntarily at a certain tension, progressively greater voluntary effort is needed to maintain it, until an end point is reached when the tension begins to fall. A maximum voluntary contraction declines in tension continuously.

It has been shown that in voluntary muscular activity lasting for short periods of several minutes, the main cause of these fatigue changes is the gradual failure, with activity, of the contractile mechanism (Merton 1954). It is clear, however, that there are other factors involved such as neuromuscular block (Brown and Burns 1949), central fatigue in the motoneurones (Reid 1928, Bartley and Chute 1947, Lovatt-Evans 1951) and possibly alterations in the linkage between action potentials and the contractile process. Although several authors state that fatigue of muscle is not associated with any change in the size and form of muscle action potentials, effects are demonstrable. First, the action potentials recorded from single muscle fibres during activity show definite changes when the muscle is fatigued. Secondly, the organization of the electrical activity recorded from the whole muscle undergoes considerable modification. Synchronization between the firing of different motor units within the muscle appears (Buchtal and Madsen 1950) and the grouping of electrical activity in ‘ bursts ’ at about 8–12 c/s becomes prominent after prolonged activity (Lippold *et al.* 1957). Migration of activity during prolonged contraction can be demonstrated to occur between one muscle and another in some movements (Lippold 1955).

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Further effects of fatigue on the electrical activity of muscle arise in connection with muscle spindles. Muscle spindles are sensitive to environmental changes, such as local ischaemia and temperature fluctuations, and it is reasonable to suppose that fatigue modifies their responses.

This paper describes some of the changes in the electrical activity of muscle brought about by voluntary fatigue.

§ 2. Methods and Procedure

The subjects for these experiments were male and female research workers, laboratory technicians and medical students, aged 18 to 30 years and of average physical fitness.

2.1. *Electrical Recording*

Records were obtained from whole muscles using surface suction electrodes of silver, 5 mm diameter. Unless otherwise stated each amplification channel employed three electrodes placed in line, an equal distance apart along the length of the muscle concerned, connected to the input of a differential amplifier having an inphase–antiphase discrimination ratio of 5000 to 1, an input impedance of 4 MΩ and an overall time constant of 5 sec (which could

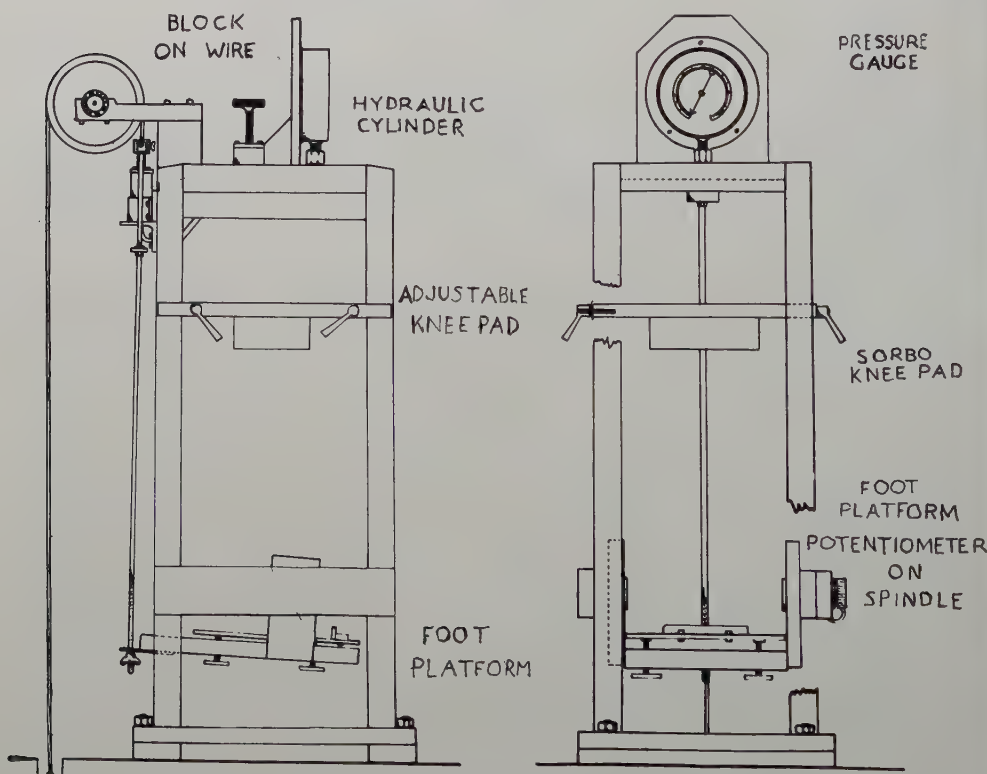

Figure 1. The dynamometer. When the foot platform is depressed the steel wire passing over the pulley raises a bucket holding the desired weight. In the horizontal position, the block on the wire contacts the plunger of the hydraulic system and further pressure is then isometrically recorded on the pressure gauge. The angular rotation of the platform is registered by the potentiometer attached to the bearing spindle.

be shortened to any desired degree). Conventional concentric needle electrodes were used to obtain localized recording from muscles. Photographs were taken on 35 mm bromide paper travelling at 30 cm/sec ; a monitor tube enabled the action potentials to be observed at the same time. Integration of the electrical activity was performed by a screen-coupled phantastron, fed from the pre-amplifier via a full-wave double diode and variable time-constant. This circuit produced pulses whose frequency was directly proportional to the area enclosed by the action potential waveform. Estimation of the degree of synchronization present in a recording was made by constructing frequency-distribution curves of the intervals between successive motor unit spikes on the continuous photographic record.

2.2. *Mechanical Recording*

Tension records were obtained from the calf muscles using the dynamometer described by Lippold *et al.* (1952). Contractions at any desired strength were made in the same apparatus but arranged so that the contracting calf muscles supported a predetermined weight, the foot being maintained at a constant degree of flexion by the subject. Figure 1 shows this apparatus ; Fig. 2 that used for measuring tension in the triceps muscle. For small hand muscles the method of Bigland and Lippold (1954) was used.

Recording of the mechanical tremor in these experiments was made with a mechano-electronic transducer which translated small changes in force exerted by the finger into an electrical record. Frequency analysis was performed by means of an Ediswan low frequency wave analyser.

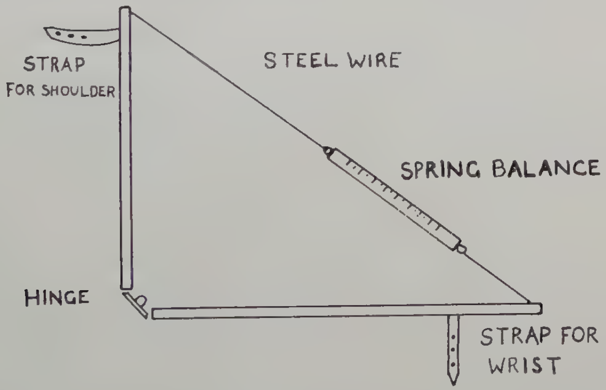

Figure 2. Method of measuring force of contraction in the triceps muscle of the arm. The frame is strapped to the upper arm and to the wrist ; extension of the elbow joint by triceps is registered on the spring balance which can be seen by the subject.

§ 3. Results

As voluntary contraction progresses, the electrical activity recorded from the muscle increases (using either surface electrodes or diffusely recording needle electrodes). At a constant tension, maintained for several minutes, the action potential spikes become closer together and the amplitude of the recording is increased (Fig. 3). This occurs in most muscles although in some

(see below) the opposite occurs because more tension is being produced by synergists. There are also changes in the size and form of the action potential and in the synchronization of firing between motor units.

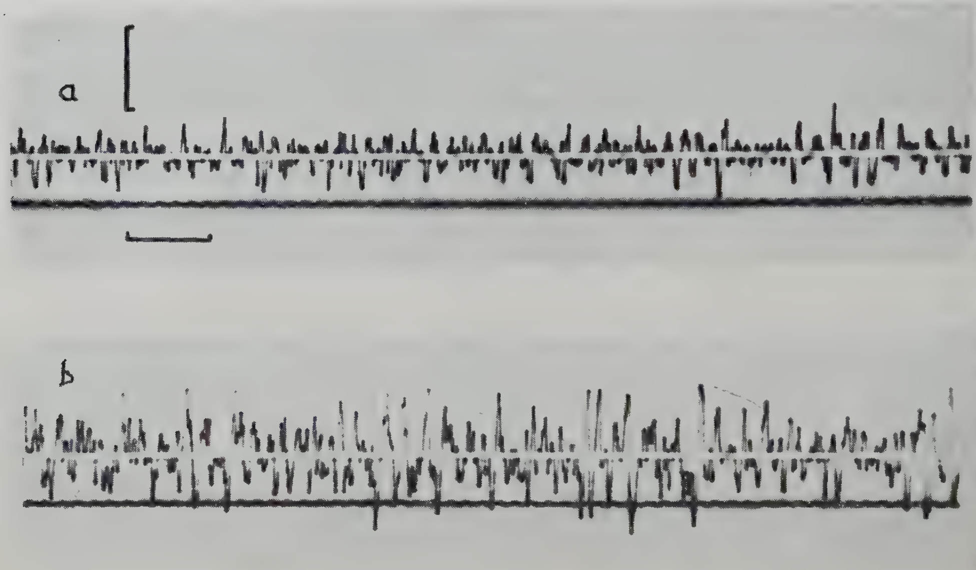

Figure 3. (*a*) Action potentials recorded at 15 sec after start in experiment of Fig. 8. (*b*) Action potentials at 4 min, 30 sec after start, Fig. 8. Time bar = 0·1 sec. Voltage calibration = 1·0 mv.

3.1. *Alteration in Form of Action Potentials*

During and immediately after repetitive activity, active muscle fibres exhibit certain changes in the action potentials accompanying each contraction. Peak to peak amplitude is reduced while the duration of each action potential is lengthened.

3.2. *Synchronization of Motor Units*

The electromyogram shows two distinct types of synchronization. In the first type, action potentials are grouped at intervals of 60–130 msec, the groups and intervals becoming more pronounced as fatigue progresses. Figure 4 shows this grouping in a record from the calf (gastrocnemius) muscle. Figure 5 is a histogram of intervals between action potential spikes taken before and after a fatiguing contraction of 75 per cent of the voluntary maximum tension. It will be noticed that after fatigue there is more activity at the shortest and the longest spike intervals, indicating an increase in the degree of synchronization.

Frequency analysis (Fig. 6) of the mechanical record after a fatiguing contraction shows a peak of activity of 6–15 c/s, usually at about 9 c/s (i.e. of the same frequency as the physiological tremor before fatigue but of greater amplitude). After prolonged contractions, slow tremor waves may also develop. A central origin is suggested by the fact that they also occur in muscles apart

from those fatigued. The close correspondence between the mechanical record and the action potentials (Fig. 4) indicates that this grouping underlies physiological tremor.

The second type of synchronization is possibly of central origin. During strong contractions and particularly after fatigue, large sinusoidal waves of a frequency about 25–30 c/s appear in the electrical record from needle electrodes (Fig. 7). This phenomenon has been investigated by Buchtal and Madsen (1950), who believe that it is due to the synchronous firing of groups of motor units.

3.3. *The Effect of Fatigue on the Integrated EMG*

In most muscles voluntarily contracting at a given constant tension the integral with respect to time of the action potentials, recorded from the whole

Figure 4. Electrical (upper) and mechanical (lower) records from extensor digitorum communis muscle of the arm after approximately five min strong contraction. The mechanical record was taken from the middle finger, increase in tension corresponding with downward deflection. Time bar 1/10 sec.

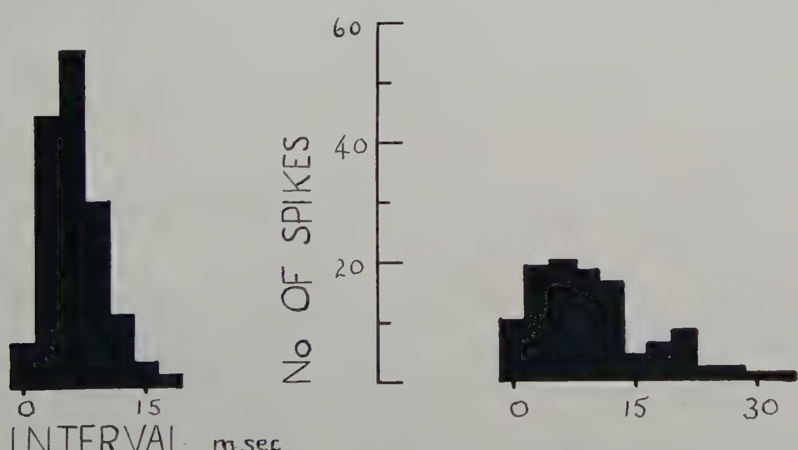

Figure 5. Histograms showing frequency distribution of intervals between motor unit spikes: Left: Normal control, recorded with concentric needle electrodes from triceps during 8 kg contraction. Right: After fatigue, identical recording conditions (5 min isometric contraction of 5 kg tension).

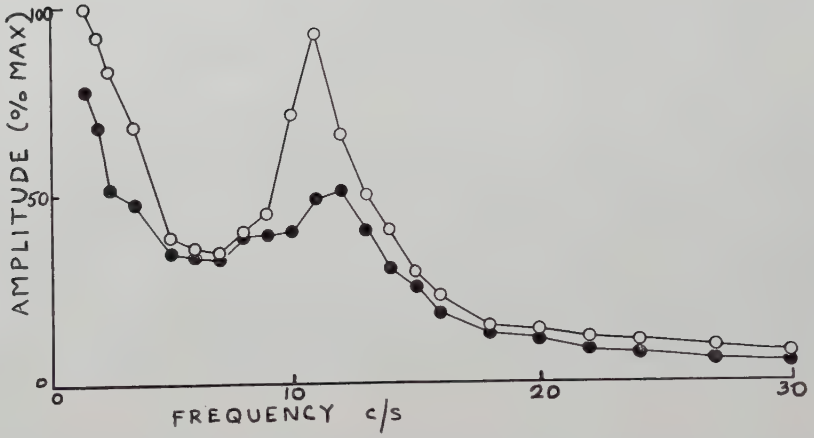

Figure 6. The effect of fatigue on tremor of the middle finger : ● = analysis before fatigue, ○ = after fatiguing contraction of same muscle (5 min ; extension of 500 g). The upward tension exerted by the finger was the same (50 g extension) in each instance.

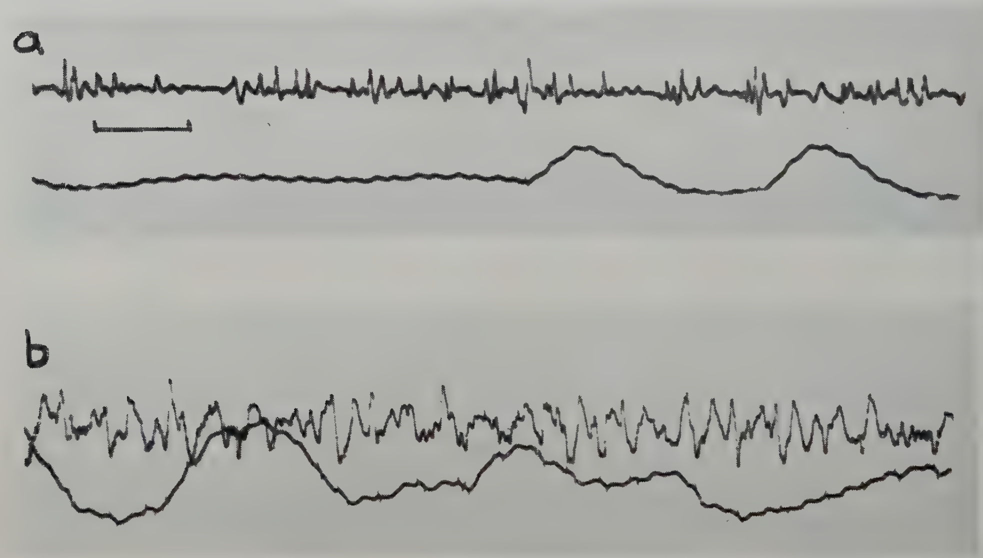

Figure 7. Electrical record (needle electrodes) from biceps muscle of the arm : (*a*) during a weak contraction and (*b*) after a strong contraction of several min duration. In both instances the lower tracings, produced for another purpose, should be ignored. Time bar 1/10 sec.

muscle, gradually increases. At a tension of between 10 per cent and 80 per cent of maximal, the integral decreases slightly during the first one or two minutes and then increases until an end point is reached, 5 to 10 min later (Fig. 8). If the strength of the fatiguing contraction is increased, the end point is reached earlier and the plotted curve is steeper (Fig. 9).

The effect is determined peripherally in the muscle and is probably the result of recruitment which compensates for the decreased force of contraction in fatigued muscle fibres. The peripheral origin of this effect can be shown by an experiment in which the blood supply to the limb is arrested by an arterial

occluding cuff, inflated at the time when fatigue has been induced. This prevents the usual rapid return of the raised integrated EMG to its normal level. Figure 10 illustrates this. The curves show the effect of fatigue on the integrated electromyogram during the course of an isometric contraction of the calf muscles at a force of 10 kg. Curve A is the normal fatigue curve, the continuous contraction ending after about 6 min, following which brief (5 sec) test contractions at the same force were made in order to obtain the three subsequent integrated action potential values. Thus when the circulation was intact, the recovery after fatigue was complete in about 1 min.

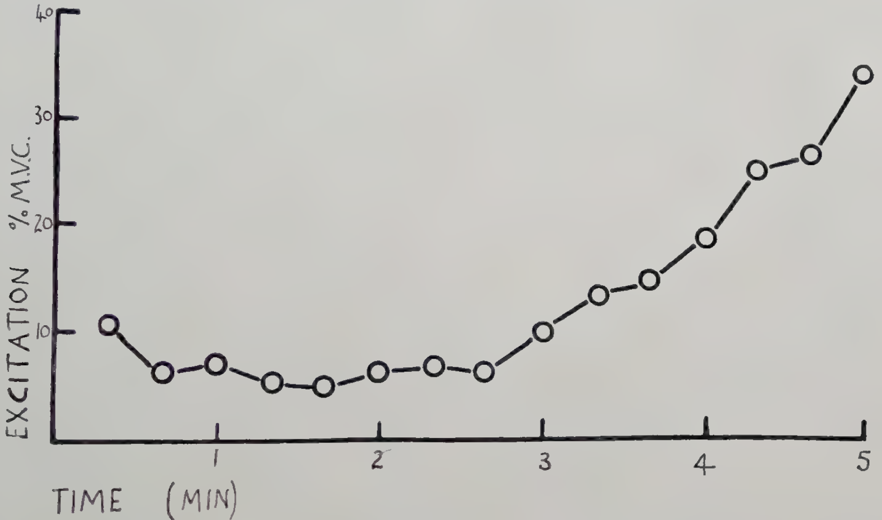

Figure 8. The time course of excitation during a constant isometric contraction of 10 kg. The excitation (A) is obtained by electronic integration of the electrical activity recorded from the surface electrodes on the belly of the gastrocnemius muscle of the calf.

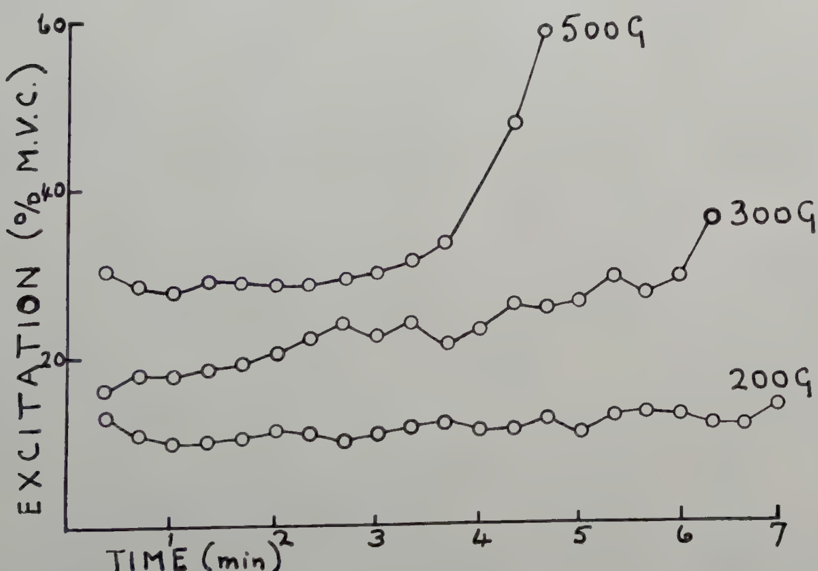

Figure 9. Effect of different rates of working on fatigue curve for abductor dig. minimi muscle of the hand with tensions of 200 g, 300 g and 500 g.

Curve C was determined similarly but at the first arrow a blood pressure cuff on the thigh was inflated to occlude the circulation to the leg and the five subsequent test contractions were made as above, with the cuff at a pressure of 200 mm Hg. At the second arrow the cuff was deflated. The integrated EMG values remain elevated and the graph shows that there is no recovery until the circulation is restored, when there is a rapid fall, similar to the curve A, on cessation of the contraction. Thus the interruption of the blood supply to a fatigued muscle prevents its recovery; the raised integrated electrical activity associated with fatigue does not fall again when contraction stops, unless the blood supply to the muscle is intact.

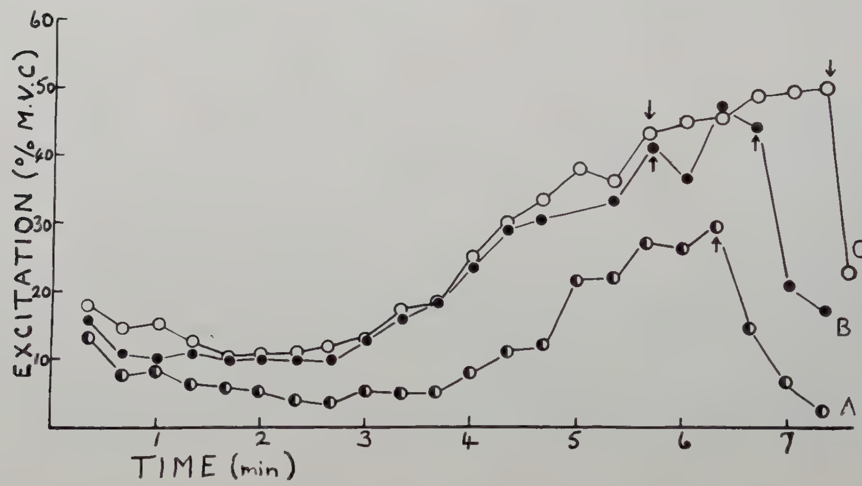

Figure 10. The effect of arterial occlusion on the time course of muscular fatigue. Isometric contraction of calf muscles at 10 kg.

Curve A=normal fatigue curve, the continuous contraction ending at 6 min 20 sec. The three subsequent values were obtained under resting conditions by recording short (5 sec) test contractions.

Curve B=fatigue curve determined in the same way but with blood pressure cuff on thigh at 200 mm Hg. At 6 min 40 sec the cuff was deflated.

Curve C=normal fatigue curve. At the end of the continuous contraction the cuff was inflated to 200 mm Hg and five test contractions made as in A with the circulation occluded. The experiment was performed in the order A, B, C at 20 min intervals. Progressive accumulation of fatigue accounts for the curves being successively higher.

3.4. *Fatigue in Different Muscles*

Central nervous organization plays a part in modifying the changes produced by fatigue in the electrical activity of muscle. Migration of activity from one muscle to another undoubtedly occurs, especially in muscles subserving skilled movement. Figure 11 shows the activity recorded from surface electrodes on extensor digitorum communis when this muscle supports a weight of 200 g hanging on the outstretched forefinger. After 5 min the activity recorded has almost ceased, yet the weight is still supported. A sharp tap on the finger, or a voluntary movement, causes the electrical activity to return. Needle electrodes show that the function has been transferred to a deeper muscle, extensor indicis proprius. A curve similar to that shown in Fig. 11 could be obtained regularly, in a number of different subjects.

A similar exchange occurs in other muscle groups, such as biceps brachii and brachioradialis and may even occur within different fasciculi of the same muscle.

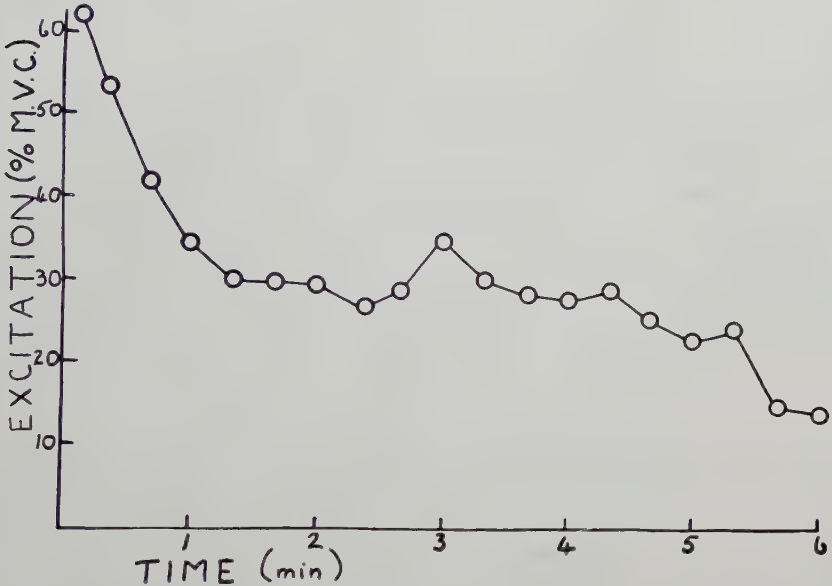

Figure 11. Decline in activity in ext. dig. comm. muscle of the arm sustaining 200 g on forefinger (see text).

§ 4. Discussion

Fatigue can occur at several points along the chain of activity from the central nervous system to the contractile process.

In the first place, fatigue occurs between the electrical excitatory system in the muscle fibre and the contractile process. From the work of Merton and others it is clear that in strong muscular contractions of short duration, the predominant effect of fatigue is here. During such contractions, individual muscle fibres exert progressively less force. Our work shows that in sub-maximal contractions compensation for this is effected by recruitment and/or increased frequency of discharge of motor units. The mechanism of this compensation is of interest in that it must involve transmission of information from the muscle to the central nervous system. A convenient mechanism subserving this function is to be found in the stretch reflex. A muscle spindle set at a given level of activity by the gamma efferent system would respond more actively if the weakening contractile force allowed the muscle to be stretched passively by a given load, and a certain amount of automatic compensation would thus be achieved. However there are no doubt other compensatory phenomena, in some cases as high as the conscious level.

The presumed increase in spindle excitation could account for the increased tremor at 9 c/s and for the greatly pronounced bursts of action potentials underlying it. There is by now strong evidence that the stretch reflex is responsible for this rhythm, because, as Lippold *et al.* (1957) have shown, the alteration of peripheral factors will modify the frequency of this rhythm;

furthermore, the interruption of muscle afferent impulses (Halliday and Redfearn 1958) abolishes the bursts.

The appearance of the electrical record in muscular fatigue is altered by three further factors:

(*a*) A change in size and form of action potentials, which become smaller in amplitude and longer in duration.

(*b*) The appearance of large waves of frequency 25–30 c/s. These may be due to the synchronous firing of neighbouring motor units. On the other hand, it is conceivable that changes in the conduction velocity in the fatigued muscle fibres might bring about the effect, or that, following prolonged activity, the membrane potential of the muscle fails to return to its normal level between successive impulses. If this occurred in a group of fibres within the muscle, these large and relatively slow potential changes might well result.

(*c*) Synchronous firing of motor units undoubtedly occurs (Buchtal and Madsen 1950), and damage is the usual cause of this (Fessard *et al.* 1948, Isch *et al.* 1950). There is a possibility that in fatigue similar functional but reversible changes occur.

The existence of neuromuscular block in muscular fatigue as normally encountered is questionable. Brown and Burns (1949) argue on the basis of animal nerve-muscle preparations that neuromuscular block depends on the amount of previous activity of the muscle. Merton (1954), on the other hand, claims that neuromuscular block does not occur in voluntary fatigue because he was unable to demonstrate any change in the size of muscle action potentials during prolonged strong contractions. He ascribes Brown and Burns' result to the fact that they were in all probability stimulating not the fibre membrane but the contractile mechanism directly.

As the contractile mechanism in a muscle weakens, central compensatory events redistribute the activity among synergists. As fatigue progresses, contraction spreads to other neighbouring muscles and even to homologous contralateral muscles (Ash 1914). Spread of excitation within the cerebral cortex seems a likely explanation for the latter phenomenon of irradiation, but no experimental evidence for this is at present available.

Looking at the variety of changes which occur during muscular fatigue it is clear that fatigue effects take place at all levels of neuromuscular organization. The relative importance of the changes is determined largely by the strength, duration and nature of the contraction. Some of the changes, in particular the weakening of the contractile process, may be regarded as primary. Others, for example the tremor and the migration of activity from one muscle to another, can be more conveniently considered as secondary in nature.

We are indebted to the Nuffield Foundation for a grant in support of this work.

Cet article discute des modifications de l'activité électrique du muscle pendant et après la fatigue: il y a des modifications de l'amplitude et de la forme des potentiels d'action; on observe une synchronisation de décharges des unités matrices.

Lors de la fatigue consécutive à une forte contraction de courte durée, on peut montrer que les modifications électriques relèvent de facteurs périphériques, principalement de l'incapacité des mécanismes contractiles à développer une tension aussi forte qu'à l'état normal. Ainsi, à mesure que la contraction se prolonge, l'activité électrique intégrée du muscle développant une tension

constante augmente progressivement. Lorsque la contraction cesse, l'activité électrique revient rapidement à son niveau antérieur à la fatigue, ainsi qu'on peut le mettre en évidence par de très courtes contractions-tests de même force. En gonflant un brassard compressif à la fin de la contraction pour interrompre la circulation artérielle dans le membre, il est possible d'empêcher cette récupération.

Le tremblement musculaire, enregistré par le mécanogramme comme par l'électromyogramme, est exagéré pendant et après la fatigue musculaire.

Die Aenderungen der elektrischen Aktivität von Muskeln während und nach Ermüdung werden diskutiert. Es finden sich Aenderungen der Grösse und Form des Aktions-Potentials; es tritt Synchronisierung der Entladungen der motorischen Einheiten auf. Es lässt sich zeigen, dass die elektrischen Veränderungen während der Ermüdung nach einer kurzen starken Kontraktion von äusseren Faktoren abhängen, hauptsächlich von der Unfähigkeit des kontraktilen Mechanismus, soviel Spannung zu erzeugen, wie im Normal-Zustand. So nimmt mit fortschreitender Kontraktionsdauer eines Muskels, der eine konstante Spannung ausübt, die integrierte elektrische Aktivität allmählich zu. Hört die Kontraktion auf, so fällt die elektrische Aktivität rasch auf das unermüdete Niveau, das durch kurze Test-Kontraktionne mit der gleichen Kraft gemessen wurde. Wird am Ende der Kontraktion die arterielle Durchblutung mit einer Drukluft-Manschette unterbrochen, so wird diese Erholung verhindert. Muskulärer Tremor, sowohl mechanisch als elektrisch registiertre ,ist während und nach muskulärer Eımüdung vergrössert.

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SOME ERGONOMIC PROBLEMS CONFRONTING THE BUILDING DESIGNER

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(Based on a paper given at the Annual Conference of the Ergonomics Research Society on 9 April 1959 in the University of Oxford)

This brief survey attempts to define broadly the scope of building ergonomics. The subject is in its infancy, and at present very much under-valued by both the architect and builder. The former prefers too often to design by eye, regardless of whether the solution is right or not, the latter to muddle on, ignoring the help that science could offer towards improving and lightening the task of the building operative, at the same time increasing his output. Further research investigations into the multitude of ergonomic problems facing the building designer and contractor are clearly required. Such studies, by reducing the number of design failures, could lead to better public regard for the architectural profession by helping them to become more competent designers. By increasing output and reducing wastage of the labour force they could help reduce building costs while, at the same time, raising the quality of building work.

§ 1. Introduction

There are two separate groups of ergonomic problems which arise in the field of building, those related to the needs of the future occupants and those related to the actual physical task of erecting buildings. Construction is the particular concern of the building contractor, and design the particular concern of the architect and his specialist advisers like the heating and ventilating engineer, and the illumination engineer. Bad design can clearly make it more difficult and possibly more dangerous to construct a building. The architect therefore has responsibilities in both fields, a point he doesn't always seem to appreciate fully. In the sphere of design, it would certainly be rash to assume that the normal architect has any formal training in ergonomic principles, though this position is being rectified to some extent for the students now passing through the University of Liverpool School of Architecture course on building science. This is, however, handicapped by the fact that the available literature is widely scattered, and not easily accessible to the architectural profession. It is therefore suggested that it would be a useful objective for the Ergonomic Research Society to try to bring together over the next few years the available ergonomic material in this sphere in a reasonably cogent and simple form for day to day use by members of the building design professions.

The clients who draft the building programme are the third important group of people connected with building design. Frequently, industrial clients well versed in the principles of work study will pass over all responsibility for a building to the architect and his specialist advisers without making beforehand any systematic or detailed studies of the defects of their existing buildings in relation to future needs. Investigations by groups like the Nuffield Foundation Division of Architectural Studies on hospitals (Nuffield Provincial Hospitals

Trust 1955) and the Ministry of Education Schools Development group, have shown how much can be learned by applying formal work study methods to existing buildings. The drafting of any building programme should clearly be preceded by a proper investigation of the needs of the work, and it is pointless for the client to assume that the architect can do all this for his normal fee. The architect has neither the time nor, it is important to add, at present the training to do it. The building is the ' total work place '. It is inconsistent for the client to devote considerable attention to the individual work place, and to ignore the wider environment, within which the particular work place will have to be located.

§ 2. Problems Confronting Workmen on Building Sites

The problems of the contracting side of the industry will be considered first. Building is essentially an outdoor occupation involving a great deal of movement of heavy and often rough materials in all types of weather, frequently at comparatively great heights. The problems of the workmen may be considered under three main headings, environmental, materials handling and placing, and safety, particularly avoiding falls.

Traditionally the attitude towards climate in the building industry has been largely one of laissez-faire as far as the environmental needs of the workmen have been concerned. Clothing is often quite inadequate, particularly now that higher buildings are more common; working on such buildings usually means greater exposure of workmen to wind with increased risk of chill, especially of the hands and feet. As a great deal of the work involves accurate placing of heavy materials that are often cold, wet and rough, adequate protection of the hands is clearly important, but difficult to achieve in practice, particularly when working with rough materials. Investigations of finger numbness (Mackworth 1953) have shown that the effects of raising wind speed from still air to only a few miles an hour are just as important in affecting performance as lowering air temperature by 9°F. The protection of workmen from wind is therefore clearly desirable in cold weather. (The thermal characteristics of the materials themselves are also important for handling in winter. Materials of high thermal diffusivity are more difficult to handle in cold weather than those of low thermal diffusivity. Timber, for example, can be comfortably handled at very much lower temperatures than dense concrete. Metals are the worst in this respect.)

General protection from cold is important for several reasons. Firstly there is a natural desire to ' shirk ' in inclement weather and productivity is lowered. Such discomfort may be due to either low air temperatures or to moderate air temperatures combined with rain and wind. Some of the larger contracting firms appear now to be recognizing the importance of proper protection against rain, and issue special waterproof outer clothing to their permanent employees. The problem of lack of vapour permeability in such clothing has not always received the attention it deserves, and serious shortcomings due to severe condensation of sweat on the inner surface of the impermeable clothing may be encountered. Such clothing may be particularly unsatisfactory in warm weather.

Falls of men and materials form the bulk of the accidents in the building industry, and cold and wet are likely to increase the risk of accidents for several reasons. Provins (1958), in his review of environmental conditions affecting driving efficiency, has discussed the ergonomic literature on the effects of cold in

detail and he notes that Russell (1957) has pointed out that some aspects of kinaesthetic sensitivity appear to be impaired at temperatures below 50°F. This may possibly affect balance and materials handling. Teichner (1958) has shown that the reaction time is longer in cold, which may mean that a slight accident turns into a serious fall instead of being checked. Thirdly Provins has remarked that one of the effects of cooling the hands is to reduce the strength in opposition of the thumb and fingers, which means that materials are more likely to slip from the grasp. The effects of water which may drastically reduce the coefficient of friction between the surfaces, are important, for such changes may easily lead to falls of both workmen and materials. In 1957 there were 14 568 accidents reported in the building industry, of which 156 were fatal. Falls accounted for 6686 accidents, 127 of which were fatal. The ergonomic factors contributing to falls would seem to merit detailed investigation. The following statement from the Chief Inspector of Factories Annual Report (1956) is significant in showing that people are unlikely to adopt safety measures if they make the task much more difficult. "In spite of the great efforts made by Inspectors to bring home to both employers and workmen the dangers when working on asbestos cement, there has been a widespread disregard of the need for proper roof ladders or crawling boards. Although these are essential for safe working, men are often deterred from using them by the extra effort, *admittedly considerable*, which is entailed in their use." Building accidents are often reported in terms like this—a man couldn't be bothered to walk down six stairs and up again to get the essential small part, e.g. a bolt or ladder to do a five-second job safely, so he took a risk. Safety measures which involve a considerable increase in the human energy cost of the job are likely to be ignored, unless the risk is excessive. Equipment needed for safety should be stored near the point where it is required when possible instead of several hundred yards away at ground level. As lifts in high buildings, as a rule in the United Kingdom, only come into operation at a very late stage in construction the energy costs of climbing stairs may present a formidable deterrent to safe practices when ground storage is used.

The metabolic cost of many building operations is high (Passmore and Durnin 1955). For example digging trenches and shovelling may involve energy costs of between 5·5 and 10·5 kcal/min according to type of soil and the height of lift. Barrow work is also energetic, particularly if ground conditions are poor, or inclines are involved. The skilled trades like bricklaying and plastering involve energy costs of the order of 4·0 kcal/min, while in joinery certain operations like hand sawing and planing have energy costs of 6·0–9·0 kcal/min. Recent trends in the building industry have been towards a greater use of mechanical power, but many jobs are still carried out by muscle power. The number of voluntary breaks appears to be high. For example, Kinneburgh and Vallance (1948) found that bricklayers were only laying bricks actively for about 25 per cent of the working day. Performance in the building industry is probably somewhat higher today, but the hard nature of such building work makes it appear probable that only limited increases of output are possible by increasing working time. It is more sensible to look for increases of productivity in terms of work reorganization and mechanization which will lower the human energy costs of different tasks. For example, Müller *et al.* (1958) have studied the transport of building materials by muscle power over short distances, reaching two main conclusions. Firstly, the piling of large units was much more economical in terms of human energy

cost than piling of small units on a weight for weight basis; secondly, piling from a 1 metre platform was much more economical than piling from the ground. Extensive studies have been made recently by the Building Research Station (Webster and McTaggart 1957) on the packaging of bricks into larger units which can be transported by crane or carried on specially designed barrows. This reduces the human energy cost in transport.

Reduction of the energy cost of the task makes the thermal environment relatively more severe in cold weather unless additional clothing is worn to provide extra insulation. This factor is likely to be found particularly important in the case of personnel who have to tend machinery, in a static position, throughout the day, e.g. tower crane operators, hoist operators, etc.

Lifting and placing of heavy materials forms a significant proportion of building work, and this is reflected in the accident statistics. Carrying, wheeling, moving or lifting by hand accounted for 19·74 per cent of the reported accidents in 1956 of which 10·30 per cent were strains and ruptures. Greater attention to correct methods of lifting is therefore important. Whitney (1958) has recently published a study of the strength of the lifting action in man. One of the most important of his conclusions from the point of view of the building industry is the marked influence of foot placement distance on the vertical lifting force, the vertical lifting force being more than halved for a change of foot placement from 30 cm to 50 cm. At present scaffolding is often used on only one side of a job, and materials may have to be placed some distance horizontally from the feet as a consequence. If the economics of bigger building units are to be realized, problems of handling will require closer attention, and techniques of scaffolding may have to be modified. Kinneburgh and Vallance (1958) have drawn attention to the wastefulness of the ‘ half load ’, the unit which is too heavy for one man, but too light for two. Manufacturers of building materials sometimes overlook the fact that men and their hands occur in integral units. The systematic study of lifting problems in the building industry on sound physiological lines would certainly seem to merit more attention. Problems of balance when carrying loads, particularly up ladders and over rough ground, could usefully be investigated as well.

It is not claimed that all the problems of the workman have been covered in this brief survey, but it is hoped that a case has been made for the serious study of building ergonomics, and that some of the larger contracting organizations may recognize the possibilities which exist in this sphere, and follow them up. Merely closing in buildings more quickly in winter could provide a more favourable environment sooner and so increase productivity and reduce accidents.

§ 3. Ergonomics and the Users of Buildings

Next will be considered problems relating to the needs of the future occupants of a building. There are at least three main classes of problems which the designer may have to consider. First, suitable physical dimensions for the building and its equipment must be selected. Second, provision must be made for a satisfactory physical environment. Third, the building must be designed so that it is convenient to use.

3.1. *Anthropometric and Postural Factors*

The sizing of rooms and the objects in them for human use has not always received the attention it deserves, and there is a common assumption among

architects that what looks right is right. In this way custom is easily confused with performance. How far wrong this intuitive approach may go is illustrated by Floyd and Roberts' (1958 a, b) review of the anatomical and physiological principles in chair and table design, which shows that the chair and table heights normally adopted as standard in this country are unsuitable for the majority of the population. In practice one frequently encounters drawers and cupboards that are too deep, working surfaces that are too high or too low, and so on.

Anthropometric problems in building would appear to fall into two types. One type is the go no-go problem where one is concerned with extremes of size distribution, for example in the selection of door heights, or the space between the chair seat and the under-rail of the table. The other type involves problems linked with the deviation about the mean, for example deciding the correct height of the seat of a chair. The problem is not to design to the average size, but to a range of sizes. The solution adopted must take into account the actual size distribution of the population who will have to use the equipment so that as few people as possible are inconvenienced by the actual solution adopted. The population may be a general one, for example in the home, or a special one, for example in a school. The anthropometric data required therefore may be those for a general population or for a special population, but in all cases it is the distribution of sizes which is important and not the mean.

Anthropometric studies cannot be rationally separated from postural physiology. For example, it is common to find benches in laboratories which are too deep for convenient use; one hand may be required to provide stability while reaching to the back. Many of the problems encountered are dynamic in nature. There is, for example, practically no information available about the carrying capacity of corridors and stairways, though some studies have been recently published by London Transport (Hankin and Wright 1958). Ergonomically, stairs should be wider than their approaches as the speed of people climbing stairs is less than when walking on the level.

3.2. *Effects of Building Design on Energy Expenditure*

Passmore and Durnin's (1955) extensive review of human energy expenditure contains many references to activities carried out in the home. Scrubbing and bed making may involve energy expenditure of over 5 kcal/min and so represent heavy work. Mechanical devices are now taking over some of such tasks in the home, but many tasks are likely to remain to be done by muscle power. It should be possible to approach design from the point of view of energy cost. This is likely to be particularly valuable in the case of dwellings for the old and the physically handicapped. The Scottish Housing Advisory Committee (1952) in a report on the housing of special groups drew attention to the physical problems of the old, particularly with bathing, stair climbing, and gardening. The majority of such difficulties could be predicted without detailed investigation from a study of existing energy cost tables. The time wasted in moving about may also be important and may represent a significant energy cost to the housewife. Such problems may be tackled along normal work study lines. For example the Building Research Station has made an extensive study of housework from the point of view of time spent in various parts of the house and distances covered (Bateson *et al.* 1954).

3.3. *Environmental Factors of Importance to the Building User*

Problems connected with the physical environment have been left until the end because they are so formidable, particularly when taken in combination. The extensive studies made in these fields have mainly been conducted by investigators interested in one single aspect of environment, say vision, thermal comfort or noise. The real problem the building designer has to face is the creation of a total environment that not only satisfies all the senses simultaneously, but which is also pleasing aesthetically. It is a pretty tough problem which invariably involves considerable compromises. For example adequate day-lighting of a tropical building may make the interior hotter due to increased radiation gains. On what principle should the designer weigh the gain in comfort due to better vision against the loss in comfort due to a more adverse thermal environment ? Again provision of adequate through ventilation which is essential for comfort in the humid tropics may lead to a severe deterioration of the acoustical environment due to extraneous noise. How should one assess this kind of problem ?

The important distinction between comfort standards which are partly formed by habit and custom, and performance standards which are based on actual physical observations is not always recognized, and the unwarranted conclusion that performance is best in the most comfortable environment is often drawn. Again one may require tolerance standards which set upper or lower limits, which can not be exceeded without dangerous consequences. It may not always be possible to make the environment comfortable, but it must never be physiologically intolerable.

There is a distinction between environmental factors for which there is a definite physical equilibrium condition, e.g. the thermal balance of the human body, and environmental factors for which there is no actual equilibrium condition, e.g. hearing, smell or vision, but a set of conditions for optimum performance. In the former case, absolute recommendations can be made which are independent of social and economic factors though such standards cannot always be economically achieved. In the case of the human energy detectors, the eye and the ear, the ‘ signal to noise ’ ratio affects performance drastically. Psychologically some people are more aware of distracting signals than others. One might summarize the position by stating that people who are used to a high standard in some particular aspect of their perceptive environment, will complain bitterly if they are given a lower standard, but people used to a low standard are unlikely to agitate for a higher standard unless they become aware that the possibility of a higher standard exists. The recent paper by Gray *et al.* (1958) on a survey of noise in three groups of flats illustrates this point very well. The group with the lowest standards of acoustical insulation produced less complaints about noise than the groups with the highest standards. This could only be accounted for in terms of their previous socio-environmental backgrounds which were much less favourable in the case of the relatively uncomplaining group with low sound insulation standards than was the case of the less satisfied group living in flats with higher standards of insulation. The same sort of remarks apply to artificial illumination standards. Lighting levels considered satisfactory in a typical working-man’s home today would be considered fantastically low in contemporary progressive office blocks. Field surveys of environmental comfort are liable to

be rather indecisive in fundamental scientific terms. Such surveys may, however, help to establish what is acceptable in any particular situation. Most comfort standards, however, are not absolute, but are related to previous and present socio-economic status, and experience.

More profitable studies on sensation can often be made using only a very limited number of subjects in intensive tests designed to throw light on the detailed working of the human sense organs. Hopkinson (1959) has preferred this type of technique in his extensive studies of the psycho-physics of vision in relation to illumination. Such studies do not enable illumination standards to be directly established for different socio-economic groups, but they systematize some of the complex factors affecting performance, and so enable design to be improved on a rational scientific basis.

Comfort, in fact, is a dangerous concept in building design, for we are only really aware of discomfort. It is the view of the writer that a particular environmental factor becomes uncomfortable only when it becomes a distraction. Motivation cannot therefore be separated from awareness of discomfort. The greater the motivation, the less important the distraction. If the unwanted signal arises directly from carrying out a particular task, it is likely to be less distracting than a signal from an extraneous source as Broadbent (1958) has shown in certain cases of noise. An extraneous meaningless signal is likely to be less distracting than an extraneous meaningful signal, particularly if there is some form of adverse emotional response to the extraneous signal. For example, hostility towards a neighbour increases the probability of him being found a noise nuisance.

Absolute standards in most branches of environmental physics do not exist—the ultimate concern is what is feasible in the light of existing technical knowledge and available economic resources.

Cette courte revue tend à définir les objectifs d'une Ergonomie du bâtiment. Ce domaine en est à ses débuts et jusqu'à présent, son importance est sous-estimée tant par les architectes que par les constructeurs. Les premiers préfèrent trop souvent dessiner pour le coup d'oeil, sans égard à l'opportunité des partis adoptés, tandis que les derniers continuent à opérer de manière confuse, ignorant l'aide qu'une approche scientifique pourrait apporter dans le sens d'une amélioration et d'un allègement des tâches des ouvriers du bâtiment aussi bien que dans le sens d'un accroissement de leur rendement. De nouvelles recherches sont certainement désirables dans tous les domaines de l'ergonomie intéressant les architectes et les entrepreneurs. De telles études, en réduisant la fréquence des défauts de conception, pourrait faire apprécier davantage la profession d'architecte. En augmentant le rendement et en réduisant le gaspillage de main d'oeuvre elles pourraient contribuer à réduire le coût en même temps qu'à améliorer la qualité de la construction.

Dieser kurze Ueberblick versucht, in grossen Zügen den Bereich der Arbeitswissenschaft in der Bauwirtschaft abzugrenzen. Dieses Gebiet ist noch in den Kinderschuhen. Es wird zur Zeit von Architekten und Bauarbeitern sehr stark unterbewertet. Der Architekt zieht es oft vor, nur mit dem Auge zu entwerfen, ohne Rücksicht darauf, ob seine Entwürfe richtig sind oder nicht. Der Bauarbeiter arbeitet, ohne die Hilfe zu beachten, welche die Wissenschaft ihm bieten kann, um seine Arbeitsaufgaben zu verbessern und zu erleichtern und zugleich seine Leistung zu erhöhen. Es bedarf weiterer Forschungsarbeit über die Fülle der arbeitswissenschaftlichen Probleme, denen Architekt und Bauunternehmer gegenüberstehen. Solche Untersuchungen können dazu führen, dass durch Abnahme der Zahl der Fehl-Entwürfe die Architekten in der Oeffentlichkeit grösseres Ansehen gewinnen. Durch Erhöhung der Bau-Produktion und durch Herabsetzung der Vergeudung von Arbeitskraft könnten sie mithelfen, die Baukosten zu senken und gleichzeitig die Güte der Bauten zu heben.

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OPTIMAL FORM AND DIMENSIONS OF HAND-GRIPS ON CERTAIN CONCRETE BUILDING BLOCKS

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The optimal form and dimensions of hand-grips for handling certain types of concrete building blocks were found by theoretical considerations and laboratory experiments. Such grips were found to reduce the physiological work-load considerably. The maximal lifting power proved to be a far better criterion for the evaluation of minor changes in dimensions of hand-grips than energy expenditure or heart rate during work.

§ 1. Introduction

In modern building practice, rationalization from technical and physiological points of view promotes the use of concrete building elements instead of bricks (Müller *et al.* 1958). Some time ago the question arose as to whether the physiological work-load, due to handling concrete blocks of a certain type, could be lightened if finger-grips were provided in addition to the existing thumb-holes. Furthermore, if this were so, what would be the optimal combination of thumb-holes and finger-grips from both the physiological and technical points of view ?

§ 2. Theoretical Considerations

The form, dimensions and weight of the blocks to be studied are shown in Fig. 1. From the more detailed longitudinal section of one part of the block in

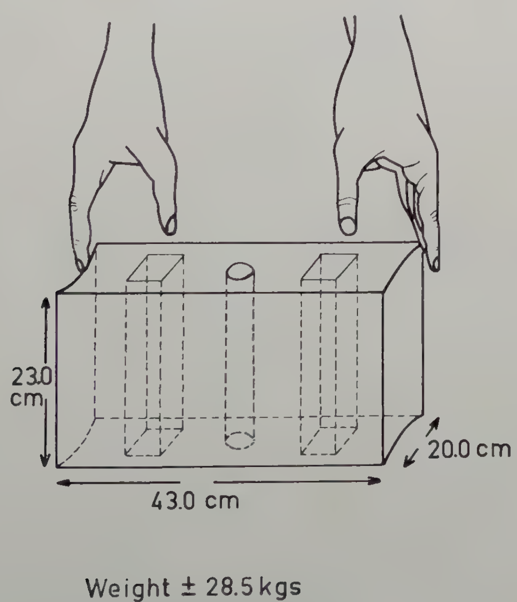

Figure 1.

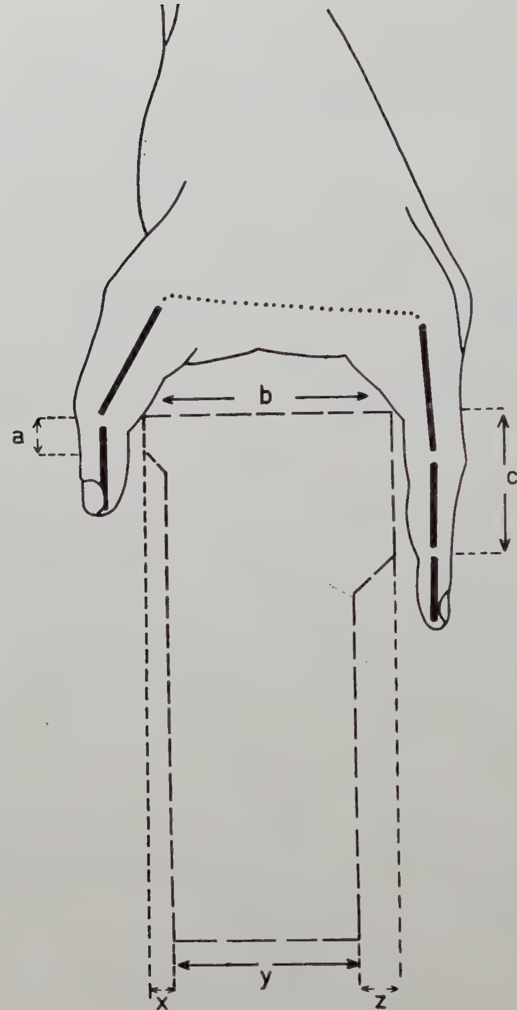

Figure 2.

Fig. 2, it becomes evident that theoretically the combination of thumb- and finger-grips can be represented by the following six variables:

a = distance from thumb-grips to upperface of block,

b = width of upper face,

c = distance between finger-grip and upperface,

x = depth of thumb-grip,

y = thickness of concrete partition between tips of thumb and fingers,

z = depth of finger-grip.

Since finger-grips would always be excavations at the ends of a block, another measure to be studied is the width of finger-grip. The minimal values of this dimension are 40 mm for two fingers and 80 mm for four fingers. The

form of the upper edge of the excavations could be straight or curved. Altogether there are eight variables to be taken into account. At first glance it would appear that an enormous number of grips had to be tested in order to trace the effect of changes in each variable separately. In practice, however, this number can be limited owing to technical restrictions and functional-anthropometric considerations. The technical desiderata were:

the upper face should be flat,

the thickness of the concrete partition y should certainly not be under 25 mm and preferably not less than 40 mm,

the depth of the finger-grips was limited.

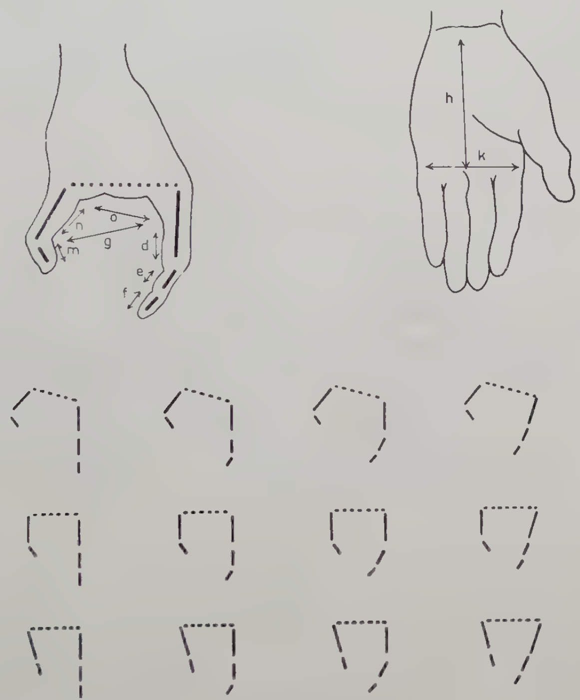

Figure 3.

The functional-anthropometric considerations are illustrated in Fig. 3. In principle, there are six functional elements in a hand-grip, namely the effective distances between finger and thumb joints (see diagram). Theoretically there are many possible positions of the hand represented by different geometrical arrangements of these six lengths. Many of these positions are ruled out by anatomical considerations and by the practical consideration that the gripping force would be too small for holding a building block. Interest was therefore limited to the twelve ways of gripping illustrated in the lower half of Fig. 3. It is obvious that, for each of the gripping positions, there are fixed values of a and c and minima and maxima for b, x and z related to anthropometric data. As practically no data are to be found in the literature, some

relevant measurements were made on 15 male adults holding their hands in several gripping positions. The results obtained were as follows:

Table 1. Summary of some functional data (in millimetres) measured on 15 right hands

	Height (cm)	Weight (kg)	h	k	m	n	o	d	e	f	g
Mean	177	71	99	81	29	29	61	29	21	23	74
S.E.M.	8·0	8·1	5·9	6·3	2·2	2·7	4·2	3·6	1·6	1·9	5·5

(See Fig. 3 for code.)

Finally a series of 29 sets of hand-grips was moulded of clay or wood. They were variations on the 12 hand positions mentioned (Fig. 3), while their dimensions were based on the anthropometric data (Table 1), taking into consideration that protective plastic gloves are worn when the blocks are handled.

§ 3. Methods of Investigation

In order to carry out experiments with the different sets of hand-grips, they were mounted upon an iron bar, loaded with a weight, in such a way that both the distance between the hand-grips and the weight of the original concrete blocks were simulated. In a preliminary experiment two subjects were studied performing a standard task with this model. The task consisted of lifting and replacing the model over a fixed height and according to a prescribed time schedule. Pulse rate and oxygen consumption during work were measured. Four hand-grips, differing only in the depth of the finger-grip were studied. The results are summarized in Table 2.

Table 2.

Depth of finger-grips z (in mm)	Pulse frequency in last 5 min of steady state		Oxygen consumption in last 5 min of steady state (ml/min)	
	Subject A	Subject B	Subject A	Subject B
19	102	101	783	648
13	110	91	845	673
4	111	123	838	753
0	119	113	934	824

From this table it is obvious that the work of handling concrete blocks can be lightened by fitting them with finger-grips. But, as there is no definite correlation between oxygen consumption and pulse rate on the one hand and the depth of the finger-grip on the other, the criteria used were considered not satisfactory for a more detailed analysis of hand-grips.

For this reason the maximal lifting power was taken as a criterion, on the assumption that high maximal lifting power correlates with good quality of grip (Schönefeld and Heising 1956, Ross 1957). Each of the 29 sets of hand-grips was now fitted with a spring ergograph. Six subjects, wearing plastic gloves, were requested to pull with each set of grips four times in succession with their maximal force. The mean of the 24 values obtained with each set was called the 'maximal lifting power' for a given set of grips.

§ 4. Results

In Table 3 the hand-grips tested are arranged according to increasing magnitudes of the maximal lifting power, while for each set of grips the actual dimensions are given. At the bottom of the table is shown the maximal lifting power, reached by means of an iron bar with a diameter of 20 mm.

Table 3.

No.	*a*	*b*	*c*	*x*	*y*	*z*	Straight or Curved	Length	Maximum lifting power in kg
1	20	50	—	5	45	0			37·4
2	0	65	—	10	55	0			37·9
3	0	50	—	5	45	0			38·3
4	0	70	—	10	60	0			38·3
5	20	50	0	5	40	5	Straight	80	41·2
6	0	50	0	5	40	5	,,	80	45·1
7	20	50	30	5	40	5	,,	80	45·1
8	20	50	40	5	40	5	,,	80	47·0
9	0	65	50	10	51	4	,,	40	48·2
10	0	50	30	5	40	5	,,	80	51·8
11	0	55	30	15	25	15	,,	80	53·2
12	0	70	0	10	40	20	,,	80	53·2
13	0	50	40	5	40	5	,,	80	53·7
14	0	70	30	15	40	15	,,	80	55·6
15	0	65	30	15	35	15	,,	80	56·6
16	0	70	30	10	40	20	,,	80	56·6
17	0	60	30	15	30	15	,,	80	57·5
18	0	70	40	10	40	20	,,	80	59·4
19	0	65	50	10	47	8	,,	80	60·4
20	0	65	40	10	48	7	,,	80	67·2
21	0	65	40	10	36	19	,,	40	71·8
22	0	65	40	10	46	9	,,	80	75·4
23	0	65	40	10	44	11	,,	80	76·0
24	0	65	40	10	42	13	,,	80	81·7
25	0	65	40	10	40	15	,,	80	82·7
26	0	65	40	13	33	19	Curved	80	83·5
27	0	65	40	10	38	17	Straight	80	84·2
28	0	65	40	10	36	19	,,	80	84·7
29	0	65	40	10	36	19	Curved	80	85·7
30		Bar instead of handgrips							115·0

When comparison is made of the results obtained by measurements of oxygen consumption and pulse rates and by determination of maximal lifting power, it is evident that the latter criterion is superior. This can be demonstrated by the fact that the differences shown in Table 2, as the depth of finger-grip is decreased, are more marked when the criterion of lifting power is used. The lifting power for each depth of finger-grip is as follows:

84·7 81·7 48·2 37·9 kg.

The superiority of the maximal lifting power as a criterion appears also from the fact that the lifting power discriminates between 2 mm changes in the depth of finger-grips z (Table 3, Nos. 20, 22, 23, 24, 25, 27, 28).

Theoretically the best hand-grip would be one with ideal dimensions for each of the variables shown in Table 3. It was indeed found that with such an ideal grip (No. 29) the highest values of maximal lifting power (85·7 kg) were obtained. This value amounts to 74·5 per cent of the maximal attainable pulling force (with the iron bar) and to more than twice the force that can be exerted on a block with thumb-grips only (No. 2), as was formerly manufactured. These results seem to be contradictory to the views of Maxwell (1957), who opposes the use of the finger-tips as being unsafe and unsuitable for lifting.

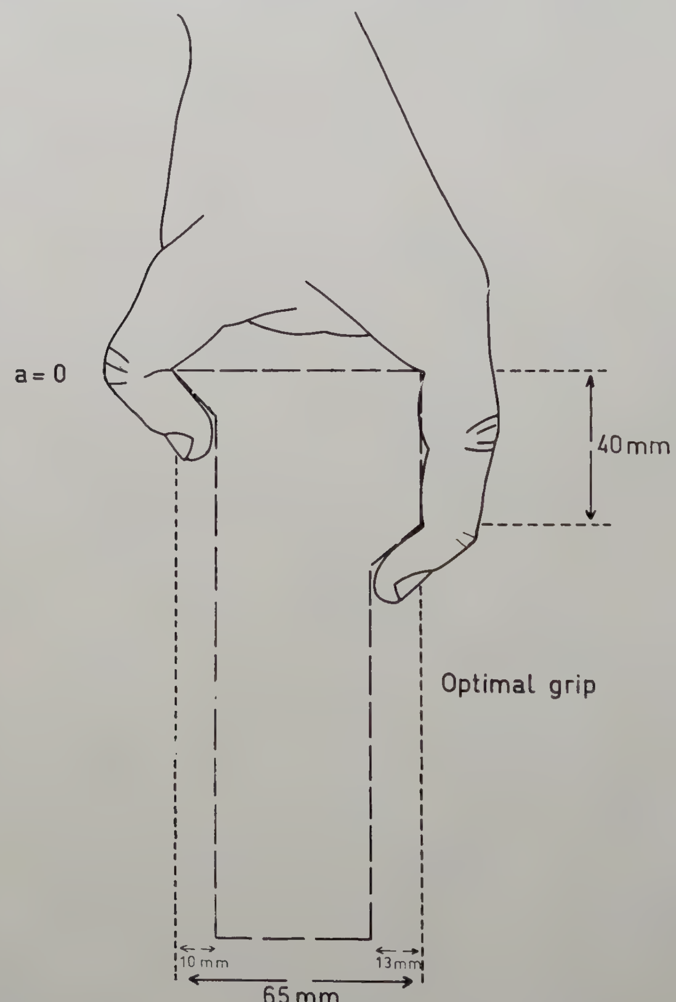

Figure 4.

For technical reasons it was finally decided that building block type No. 24 (Fig. 4) was the best solution to the problem posed by the building industry at the commencement of this study. The maximal lifting power of this differed only slightly from the ideal of No. 29.

La forme et les dimensions optimales des prises (en creux) qui servent à manipuler certains blocs de béton de construction furent mises au point, à la suite de considérations théoriques et d'expériences de laboratoire. De telles prises montrent une réduction considérable de la charge physiologique. La force d'élévation maximum se révéla d'être un meilleur critère pour l'évaluation de faibles changements dans les dimensions des prises, que la dépense énergétique ou le rythme cardiaque.

Optimale Bildung und Ausmässe von Handgriffen an groszformatigen Mauersteinen von bestimmtem Type, wurden ermittelt unter Zuhilfenahme von theoretischen Überlegungen und Laboratoriumexperimenten. Es ergab sich aus dieser Untersuchung dass die physiologische Arbeitsbelastung beim Handhaben erheblich erleichtert wurde durch die Anwendung dieser Griffe. Für die Bewertung von kleinen Variationen in Handgriffen zeigte sich der ' Maximale Zugkraft ' ein viel besseres Kriterium als die Grössen von Sauerstoffverbrauch und Pulsfrequenz während der Arbeit.

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LETTER SORTING MACHINES—PACED, 'LAGGED' OR UNPACED?

By R. Conrad

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Summary

Distinction can be drawn between three types of letter sorting machines and these types can also be used to classify other kinds of machine and task. In one type ('paced ') the speed of operation is set by the machine : in another (' unpaced') the speed is determined by the operator's own actions, and in a third (' lagged ') the speed is determined by the operator, but a minimum time (a ' time lag ') has to elapse between one operation and the next. The performance of 7 operators on a lagged letter sorting machine was observed over a period of 9 months. Records were taken of mean sorting rate, and of the distribution of sorting times. Practice effects are shown to have been continuing at the end of this period, and it is argued that the distribution of sorting times has been affected by the machine's lag.

By assuming a distribution that would be expected if there were no lag, tables are presented which estimate what the sorting rate would be (*a*) if there were no lag at all, (*b*) for different values of lag and (*c*) for different values of paced rate.

§ 1. Introduction

The transition from sorting mail by hand to sorting mechanically, has stimulated research both in engineering and in ergonomics in a number of countries. All systems now operating or nearing completion, require a human operator. His role is to extract information from an address and to encode it for subsequent machine processing. This role poses a number of psychological problems for which different solutions are being attempted in different countries (Copping and Langton, 1960).

There is, for example, the problem of displaying the envelope to the operator. A Canadian system requires the operator to look alternately at two display windows set one above the other. The Bell letter sorting machine passes envelopes in front of the operator in a stream from right to left. A Russian machine presents envelopes singly. The British single position letter sorting machine presents envelopes in two vertically arranged windows so that the operator can read ahead to the next letter, but need not.

The information which the operator is required to extract from the envelope also varies from system to system. He may have to read the name of the destination, or a coded form of it put on by the writer, or he may be concerned only with certain key letters in the destination. Again this information may be transcribed by different means into a form suitable for machine processing. It may be turned into a 3-digit code punched out on a digital keyboard, or into a 2-key letter code, the two keys being struck together; the town name, or code for it, may be copied onto an alpha-numeral keyboard; or there may be a single key for each possible destination. Problems of the physical appearance, of the operator's position and of the immediate environment also suggest a variety of solutions.

Another problem, with which this paper specifically deals, concerns the temporal character of the timing of the presentation of letters to the operator.

The designer of these systems, has broadly, three alternatives, all of which have their adherents in current practice. The system can be *paced* ; that is, the operator has no control over the rate at which envelopes are displayed before him. In this case, the designer may have to determine in advance what the rate is to be, since it may not be easy to modify it later. Because this is a relatively simple arrangement mechanically, a number of letter sorting machines are of this kind. At the other extreme, the system may be effectively *unpaced*. In this case, each letter arrives as the previous one departs. The operator is under no temporal constraints ; he works as fast or as slowly as he wishes, like a pianist or typist. A third possibility is that the system is basically unpaced, but that for engineering convenience or for reasons of cost, the speed of the machine has a fixed upper limit of speed. Work will always wait for the operator to attend to it, and he can deal with items as fast as he likes—up to a predetermined point. Beyond this point he cannot go. In other words, a minimum time-lag must elapse between dealing with one item and the next, and for this reason the system is referred to as *lagged*.

This paper describes a study which was carried out in a G.P.O. sorting office, which throws some light on the problem of the relative merits of these three systems.

The problem of paced versus unpaced work has been discussed in a general way by Conrad (1955 a). The same author (1955 b) reported an experiment carried out in a factory which defined some of the factors involved in predicting the output of paced and unpaced systems. It is clear, for instance, that when the temporal constraints are relatively loose—when the operator can effectively respond a little ahead or a little behind—paced work may yield the same output as unpaced work, if the pace is sufficiently fast. But when the time limit for response is more restricted, inevitably there are periods when the operator is unprepared to respond, and the item either waits or is not processed. Equally there are periods when the operator is ready too soon and waits for work. In unpaced systems neither of these delays occurs, and output is therefore higher. Letter sorting machines invariably involve fairly rigid time limits, since the presentation of each item and the response to it must be kept in step.

A comparison of unpaced and lagged systems has been made by Leonard (1958). He used a five-choice task with a relatively simple encoding problem, short bursts of work, and with the frequency of successive events either biased so that some items occurred more often than others in a manner analogous to that met in sorting letters, or equally distributed amongst the five alternatives. He found that subjects worked faster in an entirely free, unpaced condition than when they were prevented from responding until 0·35 sec had elapsed since the last response. The difference was not statistically significant, perhaps because there were only six subjects in each group, but Leonard nevertheless felt that enforced lag could be detrimental.

Summarizing then what little is known about temporal constraints in these situations, it would seem that any constraint that either prevents the operator from working faster, or penalizes him for working slower would lower output. The present study was undertaken to try to provide some quantitative idea of the relative size of these effects.

§ 2. Method

The investigation was centred on the British single position letter sorting machine. This provides an essentially unpaced task, but after each response, the keyboard is 'dead' for 0·55 sec. Whilst the operator therefore can work as slowly as he wishes, he cannot sort a letter in a shorter time than 0·55 sec. Because there are always two letters before him, whilst keying the code for the first address in the lower window, he can read the second address in the top window. When a destination code is keyed, the lower envelope is removed, the upper envelope comes into the lower window, and a new envelope appears in the upper window.

Destinations are allotted a 2-key code memorized during training. The keyboard consists of two horizontal rows each of six keys for the left hand, and the same for the right hand. All codes involve a left-hand and a right-hand key depressed simultaneously. There are therefore $12 \times 12 = 144$ possible unique destination codes available. During the present study, 120 of these were used.

A number of these machines were installed in the sorting office at Norwich. Prior to their arrival groups of operators had undergone a period of training using a synthetic trainer with an exact replica of the keyboard. The first such batch of seven men were selected for the present study, which began soon after they were transferred to normal operating duties with 'live' mail. Throughout the study, this group was concerned only with outgoing mail.

Two measures were taken during observation periods. Firstly, the number of letters sorted during the period was counted automatically. Secondly, an automatic record was made of the distribution of the time to sort each letter, i.e. the interval between successive effective keyings.

Observations were made on operators individually, by a permanent member of the sorting office staff who had other normal duties involving record taking in connection with the sorting machines. The observation periods were at irregular intervals from the beginning of January to October 1959, but for each man they were roughly every fortnight. The duration of these periods was between one and two hours. Any official break, and all other work stoppages during the period were noted. After a time one man dropped out, but in the middle of April 1959, he was replaced by another whose training had begun later, but whose level of performance was a little above the average of the original group.

§ 3. Results

Because observations were made at irregular intervals during the period of study, tabulated learning data would be difficult to interpret. Instead, points were taken from individuals' output curves at approximately three-monthly intervals, during January, April, July and October. The means of these points are shown in Fig. 1.

Since the men became 'operational' at the beginning of December 1958, and then only after a period of synthetic training, followed by further training on an actual machine but using dummy mail, it is interesting to note that learning continued through the year, and very possibly is still doing so although further improvements are likely to be relatively small (De Jong, 1957). This

learning effect underlines the danger of premature conclusions about the performance of even relatively simple man-machine systems : only after a year of practice did it seem worth while making the quantitative analysis which follows.

These output values are 'gross'. They represent the actual number of letters sorted during the observation period, the time of which has been adjusted for known stoppages. Inevitably some delays would have escaped observation. The values in Fig. 1 are therefore interesting primarily as production figures of local interest only. The true mean rate at which each letter was sorted would be a good deal higher than those shown. Quite apart from this distinction, a further one can be drawn between ordinary operating speeds, and those found during periodic official 20 minute speed tests. The rates found during these latter tests were about 10 letters per min higher than those given in Fig. 1.

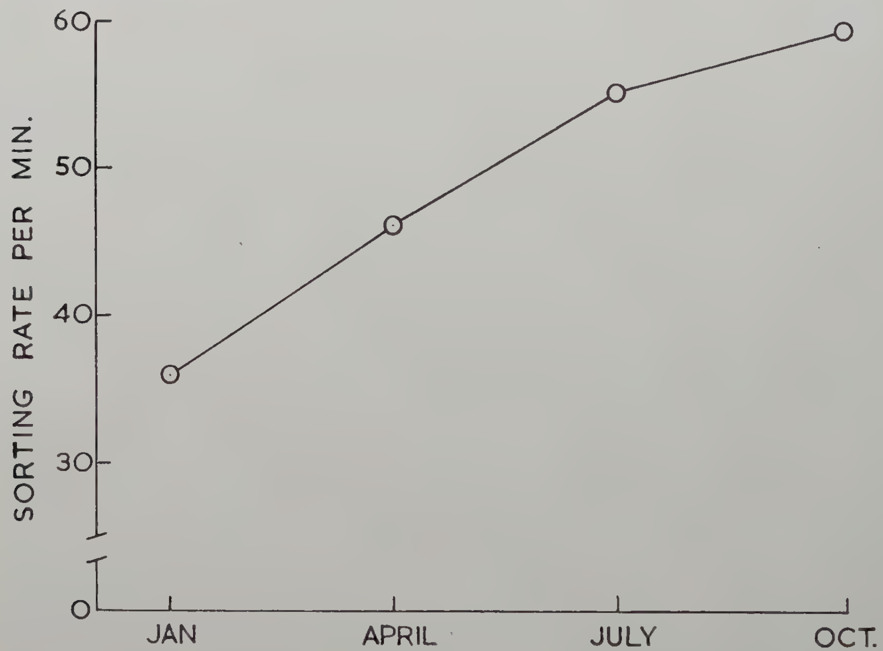

Figure 1. Effect of practice at sorting. (Means of 7 subjects.)

For a more reliable appraisal of human performance in a task of this kind one needs to look at the results of the automatic record of the interval between successive keyings. Fig. 2 shows a quite typical frequency distribution of this interval for one operator obtained towards the end of the period of study. It is immediately obvious that this is an unusually shaped distribution, since one would expect the distribution of sorting time to be approximately log-normal, which is the type of distribution commonly found with repetitive tasks (Siddall 1954, Dudley 1958). The fact that different responses are not required with equal frequency, is unlikely to affect the shape of the distribution very much (Leonard 1958), particularly in view of the extent to which the operators had practised. The implication in the present case is that the fast

end of the distribution has been artificially piled up as a result of the lag of 0·55 sec built into the sorting machine. It is therefore pertinent to ask what mean sorting rate could be expected if there were no lag, and the operator could sort as fast as he wished.

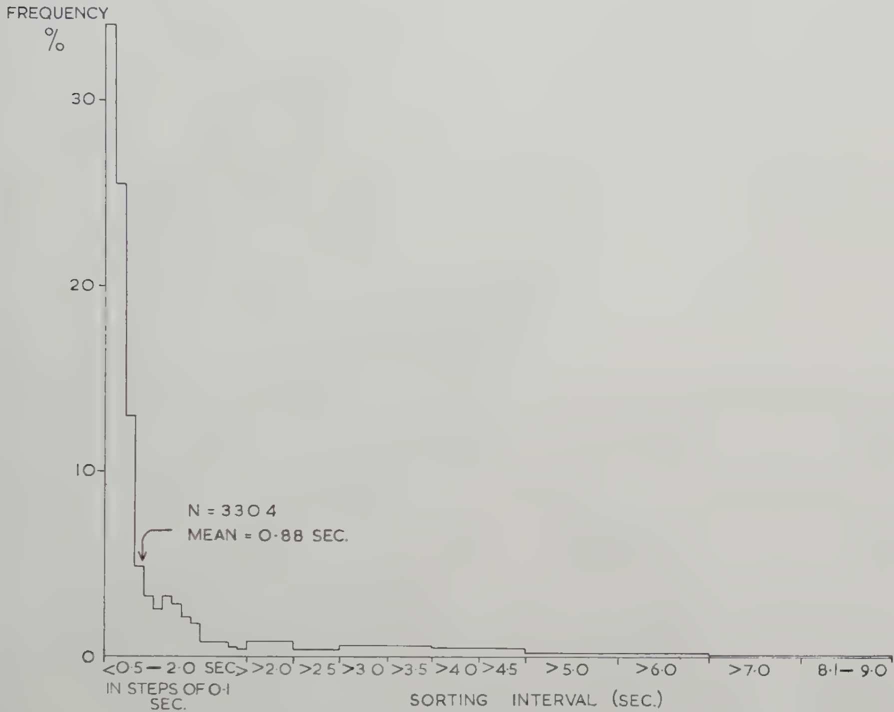

Figure 2. Distribution of sorting time for one subject.

To make this estimate one needs to invent, for each operator, the distribution that would have occurred had there been no limit on speed imposed by the machine. Rather one needs only to invent one feature of the distribution—the proportion of times that would be shorter than the mean time. In a perfect Gaussian distribution, this value would of course be 50 per cent. Some recent measures permit us to assess the required value in the present case. Siddall (1954), in an industrial task with a mean time of 1·09 sec, found about 52 per cent of times shorter than this mean. Leonard (1958) gives values for six subjects in a laboratory sorting task with a mean of about 0·4 sec ranging from 50 to 60 per cent shorter than the mean time. Dudley (1958) measured the time taken to assemble torch switches, and obtained distributions in which some 55 per cent of times were shorter than the mean. From this evidence one might justifiably assume that had the operators sorting letters been able to key as soon as they were ready, approximately 55 per cent of the resulting time intervals would have been shorter than the mean time. Table 1 shows the proportion of times shorter than the mean in the present study.

Table 1. Per cent times shorter than mean time.

Subject	A	B	C	D	E	F	G
Per cent	83·3	76·9	74·6	64·8	80·5	82·2	76·7

If an assumed value of 55 per cent is accepted, one needs merely to find the time interval on the observed distribution at which it is divided into 55 per cent shorter, and 45 per cent longer intervals, and this would be the mean time of the expected distribution. Of course this 55–45 cut is an arbitrary one—though supported by recent research. To enlarge the picture, one might make a 70–30 cut which could be taken as giving the most conservative estimate of what sorting rate would be if there were no machine delays. The true value would almost certainly fall between the two. Table 2 shows, for each operator, the observed sorting rate, and the two rates that would obtain on the basis of the two assumed distributions. The observed sorting rate, is not that used in Fig. 1, but a net rate calculated directly from the recorded distribution, which is the rate whilst the operator is actually sorting.

Table 2. Observed and estimated unpaced sorting rates.
(Items per min.)

Subject	A	B	C	D	E	F	G	Mean
Observed rate	76·5	56·6	67·4	48·7	67·4	73·0	68·4	65·4
Estimated rate if 70 per cent times were less than the mean	85·7	70·6	70·7	48·7	76·0	83·3	79·0	73·4
Estimated rate if 55 per cent times were less than the mean	92·3	82·2	82·2	57·1	83·3	93·8	90·9	82·1

When machines of this kind are designed, decisions regarding lags may turn out to involve questions of cost. Reducing time lags may become progressively more expensive, and one might want to know what increase in sorting rate could be expected. The recorded distributions provide data from which estimates can be made. Assume a lag of 1·0 sec. Then all intervals now recorded as shorter than 1·0 sec will accumulate in the 1·0 sec category. Intervals longer than 1·0 sec are unaffected. The mean time of this new distribution can be calculated in the usual way. Table 3 estimates the expected sorting rates with lags of varying duration from 1·2–0·55 sec.

Table 3. Effect of lag on sorting rate.
(Mean of 7 subjects.)

Duration of lag (sec)	1·2	1·0	0·8	0·7	0·55
Sorting rate per min	44·3	50·5	58·0	61·8	65·4

Lags in a system may prevent the operator from working as fast as he otherwise might. The effect of pacing in a system may be the same, but it may also have the effect of ‘ penalizing ’ the operator if he works too slowly. In a paced letter sorting machine, for instance, letters for which the operator is not ready at the moment when they require attention, may need special treatment. The question whether letter sorting machines should be paced or not involves factors other than psychological ones. Nevertheless the answer must again involve an assumption of the expected output. The distributions recorded in this study can provide estimates of sorting rate for different rates of pacing.

Assume a system in which a machine delivers a letter to an operator every 1·0 sec. If the operator is ready at the time, he sorts. If he is not ready, the letter passes by unsorted. All intervals now recorded as less than 1·0 sec will be available for sorting—since the operator will be ready. The intervals recorded as more than 1·0 sec will be wasted because the letter will have gone by. From the present distribution for each operator, one can therefore calculate, on these assumptions, the proportions of letters that would and would not be sorted, for different rates of pacing, and thence the output. These are summarized in Table 4.

Table 4. Effect of pacing on sorting rate.
(Mean of 7 subjects.)

Rate of pacing per min	50	60	75	86
Sorting rate per min	42·0	47·4	52·3	44·6

It should be noted that Table 4 indicates the *maximum* effect of pacing, and that the actual effects might not be as great as this. Brown (1957), with a different task, directly compared observed paced performance with expected paced performance calculated in the above manner. She found paced scores to be substantially lower than unpaced scores, though not as low as that expected by calculation.

With the proviso that Table 4 may somewhat underestimate the rates likely to be attained in a paced system, taken together with Table 3 it can be regarded as giving some idea of the probable relative performance of different systems with similar objectives. Particularly important is the fact that with paced machines there is an optimum pace beyond which output will fall. With the method of sorting studied and on the present assumptions, this would be at about 75 letters a minute, which is probably faster than would be normal for a paced machine. What seems abundantly clear is that unpaced sorting may proceed at a rate substantially faster than that which could be achieved even with the optimum fixed pace. An unpaced system with a lag, will still tend to be more efficient than any paced one, unless the lag is extremely long.

The pacing model used is, of course, a simplification of any actual letter sorting system, because in many machines, even though paced, the letters may each 'stand' in a condition of availability for a short time, providing a margin for the operator. But one should not over-estimate the value of this margin. If a system is paced at 1·0 sec intervals, the *average* time for which the item is available is one second. The operator may get a short way ahead, but he may also get behind.

§ 4. Discussion

It is hardly necessary, so obvious are they, to draw attention to the many assumptions underlying the results of this investigation. It would be quite simple to test the assumptions empirically ; it would not be difficult to compare experimentally the three systems under discussion. But it would be very costly to do so in conditions sufficiently realistic to be of value to a design engineer.

The most important assumption made, and one we may perhaps question, is that the operator's strategy would be the same in the three systems. How, for example, does a man deal with a lag ? Taking all six subjects together, some 25 per cent of all effective keyings were made within 0·05 sec of the machine's limit, and another 30 per cent during the next 0·1 sec. The shape of the distributions indicates that the operator was adapting his timing to the requirements of the machine and could often have reacted faster had he been permitted to do so. Did operators learn to judge the minimum time interval of 0·55 sec ? If so, surely some of the 30 per cent of sortings that required another 0·1 sec really belong in the shorter category, and are mis-timings rather than longer sorting times. If this were true, then the observed distributions should be even more skewed if they are to represent sorting times in an unpaced system. Alternatively, operators perhaps learned to detect an auditory cue which occurred regularly about a reaction time before the machine was clear. This again would shift the true distribution further to the short end. Leonard's subjects worked with one condition only, either lag or no lag, so that his data throw no light on this problem. These considerations do not, however, invalidate the comparison of different systems upon the basis of Leonard's data. They do not produce contrasts which are artificially great, but tend to *under*estimate the differences concerned.

What strategy is adopted for dealing with a paced system ? Brown's subjects were clearly taking very long times less frequently under paced conditions than under unpaced, perhaps hurrying over difficult items and taking time over easy ones. It is impossible to say whether the same would be true of letter sorting tasks, although it would be possible to find out by suitable systematic comparisons of paced and unpaced systems. Meanwhile calculations such as those of Table 4, which assume no change of strategy between the two systems, may be regarded as indicating the maximum deleterious effect of pacing which is likely to occur.

The fact that in a paced system an item may remain available for a period longer than the pacing interval has been discussed. Experience from factory flow line systems may not be relevant here. Generally in the factory, each item requires the same response. Thus if a response is prepared for one item, and there is no time to make it, the same response will be suitable for the next item. With paced letter sorting systems this is not the case. Letters will need different responses because they are addressed to different destinations. A response prepared for one item will not do for the next. It will need to be abandoned before the next can be prepared.

In general it seems clear that unpaced letter sorting machines ought to give a higher output than machines which either have a minimum time between one response and the next, or which are paced ; the difference being fairly considerable. Where the choice is between a lag and a fixed pace, the acceptable values of each must be taken into account. But whereas reducing the lag will always increase output, increasing the rate of pacing may lead to a drop in output. It is hoped that the data shown may be of value to designers of systems where this choice if feasible. Certainly gaps in psychological knowledge have been high-lighted which one might now hope will in the course of time be filled.

I am indebted to the G.P.O. for providing facilities for this investigation. I am also indebted to Dr. J. A. Leonard for some very valuable discussions on this subject.

On peut distinguer trois types de machines trieuses de lettres ; ces types peuvent aussi servir à classer d'autres genres de machines ou de tâches. Dans l'un des types (à cadence imposée), la rapidité de déroulement de l'opération est fixée par la machine ; dans un autre (à cadence libre), la rapidité est déterminée par les seuls actes de l'opérateur, et dans un troisième (à cadence retardée), la rapidité est déterminée par l'opérateur, mais il doit se passer une durée minimale (" un temps de retard ") entre une opération et las suivante. On a observé pendant 9 mois le travail de 7 opérateurs sur une machine trieuse retardée. On a enregistré la moyenne de tri et la distribution des temps élémentaires de tri. Les effets de l'entraînement se poursuivaient encore à la fin de cette période, et il a été prouvé que la distribution des temps de tri est influencée par le retard de la machine.

On a construit la distribution attendue en l'absence de retard ; à partir de là sont présentées des tables qui estiment ce que serait la cadence de tri si (a) il n'y avait pas de retard du tout (b) pour différentes valeurs de vitesses imposée.

Man kann zwischen drei Typen von Brief-Sortiermaschinen unterscheiden, Typen, die auch zur Klassifikation anderer Arten von Maschinen und Aufgaben verwendet werden können. Bei der einen Type ist die Geschwindigkeit, mit der die Briefe dem Sortierer vorgeführt werden, durch die Maschine bestimmt. Bei der zweiten Type bestimmt der Sortierer mit seinen eigenen Handlungen diese Geschwindigkeit, und bei der dritten Type ist gleichfalls diese Geschwindigkeit vom Sortierer abhängig, jedoch muss eine Minimalzeit zwischen einer Operation und der folgenden ablaufen. Die Leistung von sieben Sortierern an einer Briefsortiermaschine mit Minimalzeit wurde während einer Periode von neun Monaten beobachtet. Es wurden Aufzeichnungen über die mittlere Sortiergeschwindigkeit und über die Häufigkeitsverteilung der Sortierzeiten gemacht. Ein Einfluss der Übung setzte sich bis zum Ende der Beobachtungsperiode fort. Es wird argumentiert, dass die Häufigkeitsverteilung der Sortierzeiten durch die Minimalzeit der Maschine beeinflusst wurde.

Unter der Annahme einer Häufigkeitsverteilung, die zu erwarten wäre, wenn keine Minimalzeit vorhanden wäre, wurden Tabellen ausgearbeitet, die schätzen, wie gross die Sortiergeschwindigkeit wäre, (a) wenn gar keine Minimalzeit bestände, (b) für verschiedene Werte der Minimalzeit und (c) für verschiedene Werte einer vorgegebenen Geschwindigkeit.

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MANY MESSAGES FROM FEW SOURCES

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Two methods of presenting a given number of visual messages have been compared. (1) Each message was displayed by a separate source. (2) All combinations of n sources were used to display $2n$–1 alternative messages. These were called Separate Sources (S) Displays and Combined Sources (C) Displays, respectively. Comparisons were made between displays of 3, 7 and 15 alternative stimuli. The criteria of efficiency were speed and accuracy of verbal response. At the 3 and 7-choice levels there was no significant difference between the rates of gain of information from the two types of display. At the 15-choice level, subjects gained information significantly more efficiently from the S display. It is concluded that C displays can be used to advantage in signalling systems which must present up to 7 alternative stimuli.

§ 1. Introduction

A given number of visual messages may be presented in two ways which are fundamentally different. (1) A display may consist of a number of sources, each of which can present a signal which has a unique meaning. (2) Alternatively, a display may consist of a smaller number of sources, which can be combined in different ways to present the same number of signals as in (1). In general, a total of 2^n–1 signals for action can be presented by using, in turn, all of the combinations of n sources with the exception of the combination ‘ all sources off ’, since the observer cannot then tell when the signal appears. This alternative system utilizes a two-dimensional stimulus code, as each code symbol is defined by specifying a combination of two stimulus characteristics, in this case (a) the number of sources employed and (b) their position. Throughout this report the two types of display are referred to as ‘ Separate Sources ’ (S) Displays and ‘ Combined Sources ’ (C) Displays, respectively.

An important practical application of C displays would be to attempt to increase the number of easily-discriminated alternative signals from systems which employ coloured signal lights. In a report by the International Commission on Illumination on the identification of coloured lights (1959), it is concluded that an ideal signalling system should have no more than three colours to be distinguished. If more than three distinct signals have to be presented, it should be by using pairs of coloured lights suitably spaced apart, rather than by presenting intermediate colours. C displays of this kind have advantages in conditions of poor visibility, where positional cues, colour differences, etc., of S displays become difficult to discriminate at higher choice levels. The limitations of this type of display are unknown. Further advantages may be derived from the reduced size of the display. This reduces the time which is required to search the display and may also reduce the apparatus needed to generate the required information. The effect of ‘ funnelling ’ of attention, which was noted by Drew (1940) to occur with fatigued subjects, might also be eliminated in certain cases, as a large number of different signals can all be displayed within central vision.

The principal disadvantage of C displays is that the simultaneous presentation of two or more signals is precluded. This may be important where there

are large differences in signal priority, but otherwise may not be critical, particularly if responses cannot be made simultaneously in any case. A second possible disadvantage is that stimulus-response compatibility may be low, compared with S displays. A third possible disadvantage is that the failure of a single source affects all combinations which include it. This is purely an engineering problem, which can be solved by providing a simple alarm system to warn the observer of the fault, or to switch to an emergency set of signals.

Thus the advantages of C displays stem from the connection between their reduced size and established facts of visual perception. The disadvantages depend upon signal priorities.

The object of the present experiment was to compare S and C displays by studying choice reaction times in the two systems.

§ 2. Method

Displays were compared at the 3-choice, 7-choice and 15-choice levels, with speed and accuracy of response the criteria of efficiency. In order to obtain these different numbers of alternative stimuli, the C displays consisted of 2, 3 and 4 sources respectively. Simple reaction times were also obtained as a reference point for both types of display. In order to obtain a stimulus-response code which was capable, by extrapolation, of dealing with any number of alternative stimuli without basic changes in compatibility, responses were made verbally. A simple number code was used throughout, the subject responding ‘ one ’, ‘ two ’, ‘ three ’, and so on to ‘ fifteen ’, as appropriate. A disadvantage of the verbal response is that the different speech sounds involved in speaking different numbers introduce variability into the measurement of response time. This factor was unimportant in the *comparison* of displays, as the same responses were used in each, but it affects the study of choice reaction time within each display. In order to obtain a measure of this variability a further simple reaction time task was presented, in which the response was varied from ‘ one ’ to ‘ fifteen ’.

To avoid the effects of transfer of training and because of the limited period during which the experimental subjects were available, each subject performed at one choice level to one type of display only. There were therefore 6 groups, each of 8 subjects, in the main experiment, one group of 8 subjects in a test of simple reaction time with response ‘ one ’, and one group of 6 subjects in a test of differences between the 15 responses. Subjects were assigned to the several groups at random.

The subjects were 62 naval ratings, between the ages of 17 and 24, who had volunteered for psychological experiments.

The signals were presented by 5 watt neon lamps, which were displayed through 1 in. diameter apertures in a matt black surround. Figure 1 shows the way in which these sources were arranged to give the required number of alternative signals in S and C displays respectively.

The 15 sources of the S display occupied an area of 16·5 in. wide by 7·5 in. high. 3 and 7 signals were displayed by masking irrelevant sources, as shown, and adjusting lamp connections. A separate C display was used at each choice level. Sources lay within an area of 6·5 in. square.

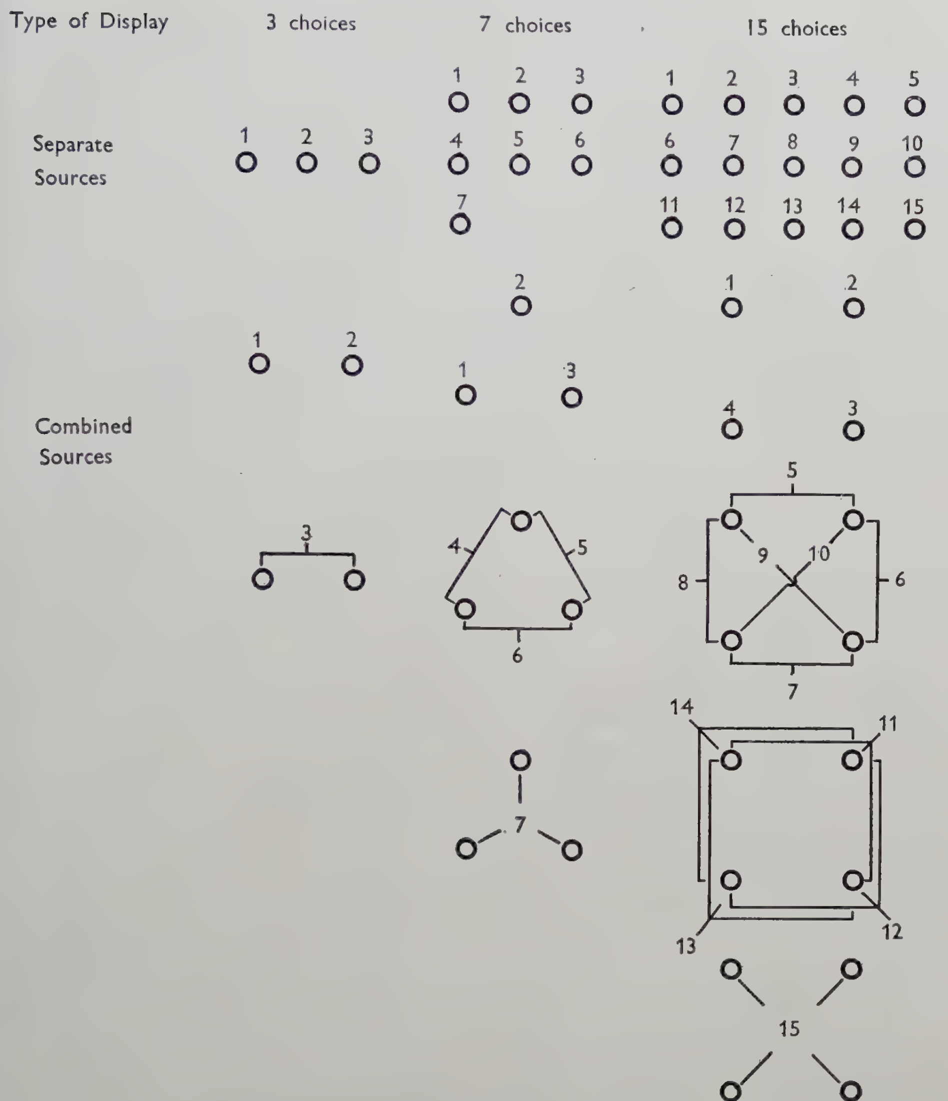

Figure 1. The displays and the response code.

With both systems, the neon lamps were energized through the points of a uniselector so that the display could be programmed to present 24 signals in any prearranged order. Connections were made through plugs and sockets in order to facilitate rapid organisation of the next signal programme. The experimenter had two keys, the first of which moved the uniselector to the next signal connection but did not alter the display. The signal was presented by pressing the second key, which was noiseless. This key also started the dekatron timer with which reaction time could be measured to 1/100th sec. The subject responded by speaking the appropriate code number into a hand microphone. This was connected to a voice key, the contacts of which stopped the dekatron timer and removed the signal from the display. The timer was returned to zero by the next depression of the first key which set in the next signal. Included in Fig. 1 is the response code which was adopted with

each display. This code followed normal reading practice with S displays and was of a circular type with C displays. Thus both codes could be extended to include any number of alternative signals, without altering the basic method of coding. The code numbers were not marked upon the face of the display, but were associated with the appropriate stimulus during training.

§ 3. Procedure

The subject was seated 10 ft from the appropriate display, which was then at eye-level. At this distance the largest display (S with 15 choices), subtended a horizontal visual angle of approximately 8°. The experimenter explained the signal-response coding until this was clearly understood. The subject was told that his reaction time was to be measured and that he must respond to the onset of the neon lamps as quickly as possible, with the minimum number of errors. Six responses were made in order to demonstrate the procedure. A sequence of 24 signals was then presented and the subject's reaction times were recorded. The noise of the uniselector movement when the experimenter pressed key number 1 was used as a ' ready ' signal. The experimenter pressed key number 2 two seconds later. If the response was incorrect, the experimenter spoke the correct number. If the response was correct, the next signal was given. Signals were presented at approximately 5 sec intervals. The procedure for obtaining simple reaction times was essentially similar to this, with the exception of the warning interval, which was varied randomly from 1·5 sec to 2·5 sec.

Four sequences of 24 signals were presented per day, with rest pauses of 2 min between sequences. Subjects for the 3-choice and 7-choice conditions were given 20 sequences in all, making a total of 480 responses. Those for the 15-choice conditions were allowed practice in responding to parts of the display. The S display of 15 signals was built up over three days, one row of lamps being learned each day. The C display of 15 signals was also built up over three days: on the first day single sources were learned; on the second two-source combinations, and on the third three and four-source combinations. Following the practice days, 20 sequences of 24 signals were given using the complete displays.

Signals appeared in an order which was determined by drawing cards without replacement, with the constraint that the same signal was not presented successively more than twice. Each signal of the 3-choice displays appeared 8 times in each sequence. This equality within sequences could not be achieved exactly with 7-choice and 15-choice displays, but in the long run all signals appeared an equal number of times.

Knowledge of results was given to the subject in the form of a learning curve which was plotted through his average score of reaction time in each test sequence. This information was given on the day following that on which the score was obtained. The number of errors made in each sequence was also given at this time, although the subject was notified immediately when his errors exceeded 5 per cent. This procedure, and the use of short test sequences, appeared, from subjects' introspective reports, to be successful in maintaining a high level of interest in this essentially monotonous task.

Procedure with the subjects who were tested in order to determine the variability in reaction time which might result from the use of the 15

different response words was the same as that for the measurement of simple reaction times already described, except that 30 responses were recorded from each subject for each response word.

As part of their general programme, the subjects were given the AH4 intelligence test designed by Heim (1955). The results of this test were available during the middle of the experiment and were noted for subsequent investigation, but could not be used in allocating the subjects to conditions.

§ 4. Results

Mean reaction times for all 8 subjects in each group are plotted for successive test sequences in Fig. 2.

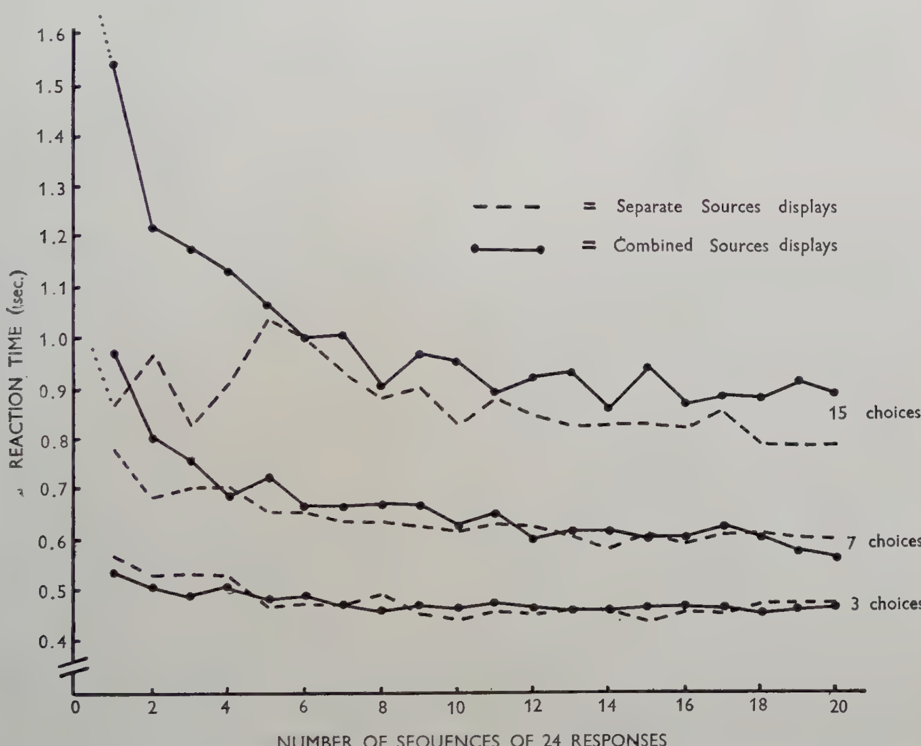

Figure 2. Learning curves at different choice levels with S and C Displays.

Very little learning occurred after the first 15 sequences (360 responses) of each condition. Subsequent analyses therefore deal with only the last 200 responses of each subject.

Table 1 shows the percentage error in each of the experimental conditions, during these final 200 responses.

Table 1. Mean Percentage Error in Choice Reactions

Number of Choices	Separate Sources (S)	Standard deviation between Subjects	Combined Sources (C)	Standard deviation between Subjects	$S + C$ Pooled	Standard deviation between Subjects
3	0·69	1·30	0·56	0·50	0·63	0·98
7	1·69	1·14	2·06	1·78	1·88	1·46
15	1·62	1·16	1·62	1·12	1·62	1·16

At each choice level there was no significant difference between the percentage error which was incurred in responding to *S* and *C* displays (Mann-Whitney U test, in Siegel 1956, p. 116). When errors at each choice level were pooled for the two types of display, the Kruskal-Wallis one-way analysis of variance (Siegel, p. 184) revealed significantly more errors ($p. = 0{\cdot}04$) with 7 and 15 choices than with 3 choices. Inspection of the nature of these errors, with 15 choices, revealed that with both *S* and *C* displays, 93 per cent resulted from responses being appropriate to the stimulus which was adjacent, in position and/or in the stimulus code, to the one displayed.

Table 2. Simple Reaction Time and Choice Reaction Time for 3, 7 and 15 alternative stimuli. Times in m. sec.

Number of possible stimuli	Amount of Information in the display in bits per stimulus	Separate sources	S.D. between subjects	Combined sources	S.D. between subjects
1	—	265	27	—	—
3	1·585	453	23	460	44
7	2·808	608	65	615	46
15	3·907	822	55	905	57

The data in Table 2 are the means of 1600 reaction times. ‘ Between display ’ differences were tested at each choice level by the Mann-Whitney U test. The difference was not significant with 3 or 7 choices, but with 15 choices mean reaction times with the *C* display were significantly longer ($p = 0{\cdot}014$) than with the *S* display. This difference could have resulted from either or both of two features of the *C* display. Firstly its code was two-dimensional in that it required discrimination of the number of sources in addition to position. Secondly it may have been more difficult to discriminate position as the number of sources employed by a signal from the *C* display increased: for example, some subjects reported that it was more difficult to discriminate positional differences when there were 3 sources than when there were only 2.

In order to test the effect of these factors, reaction times for responses ‘ one ’ only, in the *C* and *S* displays, were compared. If the first is a sufficient explanation of the observed difference, then it would be expected that the difference in reaction times for response ‘ one ’ would be of the same order as the difference between reaction times for all responses. Initial discrimination of the number of sources, which was essentially a 4-choice task, would be expected to add a constant to all reaction times. Also the test excludes any effect due to the second possible factor. It was found that reaction times for response ‘ one ’ with the *C* display were, on average, 12 per cent higher than the corresponding reaction times with the *S* display ($p = 0{\cdot}014$, Mann-Whitney test). It was concluded that the observed difference between reaction times with 15 choices resulted from the fact that a response to the *C* display necessitated two decisions, whereas only one decision was needed in order to respond to a signal from the *S* display.

Data from each display were considered separately and differences between reaction times at each choice level were tested by the Kruskal-Wallis one-way analysis of variance. These differences were significant within both the *S* and *C* displays ($p < 0{\cdot}001$). Reaction times increased with an increase in the

number of alternative stimuli. Two irrelevant factors could have contributed towards these differences in reaction time: (*a*) the differences between individual speech sounds and (*b*) intelligence differences between groups of subjects. The effect of differences between speech sounds was tested by obtaining the mean score of simple reaction time for each of the three groups of responses 'one' to 'three', 'four' to 'seven' and 'eight' to 'fifteen'. The actual differences between the mean scores of these groups were less than 10 m sec and were not significant (Wilcoxon tests in Siegel, p. 75). Therefore differences in speech sounds could not have caused the observed significant differences in reaction times among 3, 7 and 15 choices.

Intelligence differences between groups are shown in Table 3.

Table 3. Mean Group Scores on the AH4 Intelligence Test

	Number of possible stimuli presented to the Group			
Displays used by the Group	1	3	7	15
Separate Sources	82	76	80	79
Combined Sources	—	74	70	78

The higher average scores of the group which used *S* displays were not significantly different from the average scores of the group which used *C* displays (Mann-Whitney test) and there were no significant differences between choice levels within each display (Kruskal-Wallis test). Correlations between AH4 scores and reaction times, at each choice level, were extremely low and not significant, except for the *S* display of 7 choices, when low reaction times were associated with high intelligence. (Spearman's $\rho = -0{\cdot}88, p < 0{\cdot}02$).

In the *C* displays there was an almost linear relationship between reaction time and the number of alternative stimuli. Therefore the suggestion that signals were identified by some systematic visual search process cannot be dismissed. However, the data from *S* displays were not linear, when plotted against the number of alternative stimuli. In Fig. 3 reaction times are plotted against the amount of information in the display, which permits the displays to be compared in terms of rate of gain of information.

The linear function 'Reaction Time $= 190 + 158 \log \mathrm{N}$' was fitted to the mean scores of choice reaction time to *S* displays. The difference between the intercept of this curve and the observed reaction time of 265 m sec was significant ($p = 0{\cdot}01$, Wilcoxon test). This difference could have been the result of insufficient practice, at the higher choice levels, in dealing with the increased difficulty of stimulus and response discrimination. Following Bricker (in Quastler 1954), the rate of gain of information was taken as the reciprocal of the slope constant. As the incidence of errors was very small for all conditions (see Table 1) complete information transfer was assumed for the present purpose. The rate of gain of information was found to be 6·3 bits per second, up to the experimental limit of 3·907 bits per stimulus. This rate was obtained with *C* displays up to an observed limit of 2·808 bits per stimulus. It should be noted that the difference between the intercept of the curve for the *S* displays and the simple reaction time disappears if reaction time is plotted against $\log (\mathrm{N}+1)$, as suggested by Hick (1952), instead of against $\log \mathrm{N}$.

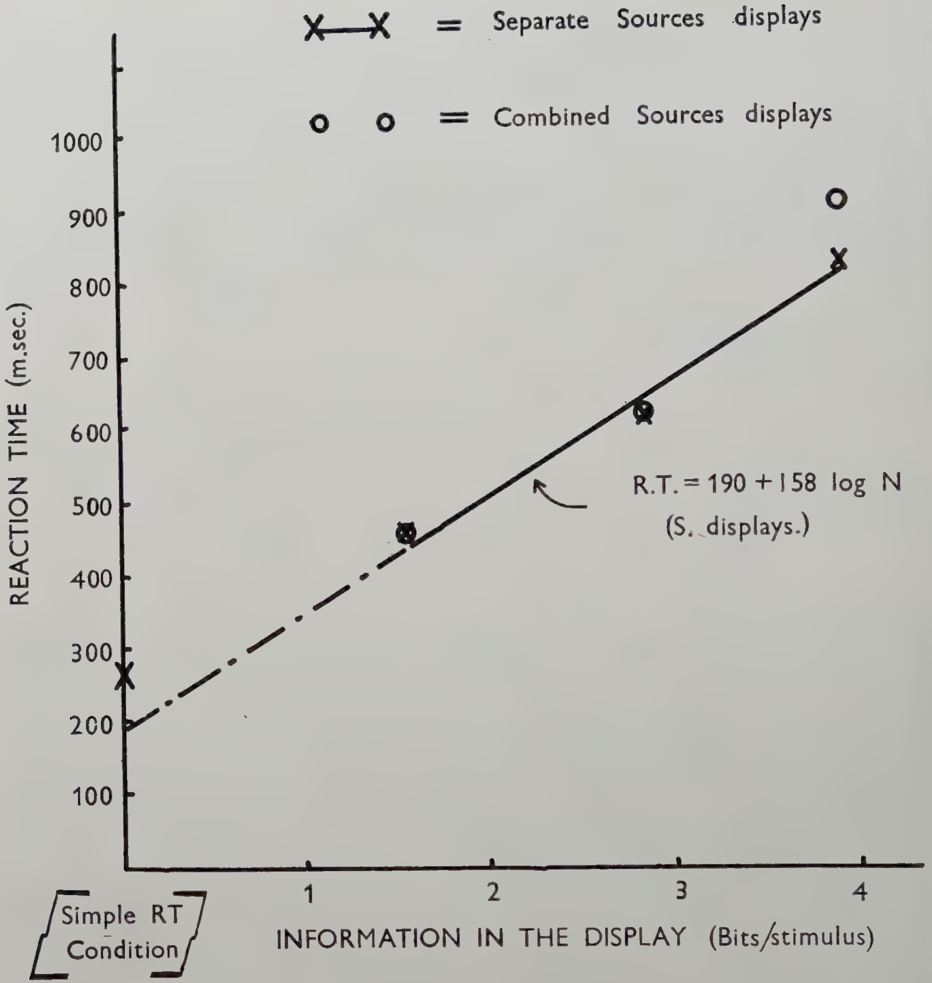

Figure 3. Choice reaction times and amount of information in the displays.

§ 5. Discussion

5.1. *Differences between Displays*

The main finding is clear-cut. When up to 7 alternative stimuli were presented, the *S* and *C* displays were equally efficient, by the criterion of reaction time. However, when 15 alternative stimuli were possible, the *S* display showed a significant advantage over the *C* display.

It can be seen from the learning curves of Fig. 2 that initial differences in reaction time between *S* and *C* displays increased greatly as the number of alternatives was increased. The work of Garvey and Taylor (1957), on the effects of task-induced stress, indicates that these initial differences may reappear under stress even when, following long practice, performance at the different conditions is equal when no stress is present. Therefore the use of *C* displays which present more than about 7 alternatives would appear to be inadvisable, at any rate in stressful situations, unless stimulus-response compatibility was of a much higher order than that tested in the present

experiment. At the same time, the use of C displays for alternatives up to about 7 appears to have practical advantages, although further work on stimulus-response compatibility at high choice levels is necessary if full advantage is to be taken of C displays.

5.2. *Differences between Choice Levels*

The curve of reaction time against the amount of information in the displays must be discussed briefly, in view of the work of Leonard (1954 and 1959), Mowbray and Rhoades (1959) and others whose work has been reviewed by Leonard (*op. cit.*). This work shows that the slopes of these curves are greatly affected by practice and stimulus-response compatibility and may, perhaps, even reach zero with long practice. The present results show little difference of slope for different degrees of compatibility and thus disagree with those of Leonard and of Mowbray and Rhoades. There seem to be three possible reasons for this:

(i) The subjects in the present experiment had relatively little practice.

(ii) The stimulus-response relationships were in both cases symbolic in that verbal responses were used. Leonard (personal communication), suggests that " the reciprocals of these slopes are in no sense measures of channel capacity, but rather reflections of doubts about which response should be allocated to a given and identified stimulus ", and that " the slopes are only indirectly related to the uncertainty which results from varying the number of alternatives". The fact remains that this uncertainty appears to be dealt with in a lawful manner.

(iii) One objection can be raised about the methods of the experiments in which zero slopes have been found. If the same subject performs at each of the choice levels tested, and is practising each number of choices concurrently, he may find it extremely difficult to adjust his anticipatory set to the relevant number of choices which are displayed. In this event, it is possible that his choice reaction time may be more appropriate to the maximum number of alternatives, at all choice levels. This would tend to produce zero slopes. In the present work, separate groups of subjects were tested at each choice level, which overcomes the objection.

This work was carried out under the direction of Dr. N. H. Mackworth and Mr. C. B. Gibbs. Thanks are due to Dr. E. C. Poulton and Dr. J. A. Leonard for guidance and to Dr. M. Stone for statistical advice. The provision of subjects by the Royal Navy is gratefully acknowledged.

On a comparé deux méthodes de présentation d'un nombre donné de messages visuels. (1) Chaque message a été présenté par une source distincte. (2) On a utilisé toutes les combinations de n sources pour produire $2\,n{-}1$ messages éventuels. On a appelé ces dispositifs de signalisation respectivement Sources Séparées (S) et Sources Combinées (C). On a comparé entre eux des dispositifs de signalisation à 3, 7 ou 15 stimuli éventuels. Les critères de l'efficience furent la rapidité et la précision des résponses verbales. Pour les choix de niveaux compris entre 3 et 7 signaux, on n'a pas constaté de différence significative entre les gains d'information provenant des deux types de dispositifs de signalisation. Mais au niveau des choix entre 15 signaux, les sujets obtenaient un gain d'information d'une manière plus efficiente à partir d'un dispositif de signalisa-

tion du type S. On en a conclu que les dispositifs de signalisation du type C sont d'un emploi avantageux dans les systèmes de signalisation qui ne doivent pas dépasser le niveau des choix entre 7 stimuli éventuels.

Zwei Methoden der Darbietung einer gegebenen Zahl optischer Nachrichten wurden verglichen: (1) Jede Nachricht wurde mit einer getrennten Quelle geboten. (2) Alle Kombinationsmöglichkeiten von n Quellen wurden verwendet um $2n$–1 wechselnde Nachrichten zu bieten. Es wird entsprechend zwischen Darbietung getrennter Quellen (S) und Darbietung kombinierter Quellen (C) unterschieden. Es wurden Darbietungen von 3, 7, und 15 wechselnden Reizen verglichen. Als Kriterium der Leistungsfähigkeit dienten die Geschwindigkeit und die Genauigkeit der mündlichen Antwort. Bei 3 und 7 Wahlmöglichkeiten bestand keine signifikante Differenz zwischen den beiden Methoden in Bezug auf die Geschwindigkeit des Gewinns an Information. Bei 15 Wahlmöglichkeiten gewannen die Personen deutlich mehr Information bei der S-Darbietung. Es wird geschlossen, dass C-Darbietungen in Signal-Systemen mit höchstens 7 wechselnden Reizen vorteilhaft benutzt werden können.

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CHANGES WITH AGE IN THE SPEED OF PERFORMANCE ON A DIAL SETTING TASK

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An experiment is reported which was concerned with the influence of ageing and the effects of precision of manipulation on the duration of movements. Two different age groups were compared on a task in which two dials had to be set alternately. The precision required to adjust the dials was systematically varied. A marked increase with age was noted in the time taken to adjust the dials, but a much smaller increase was observed in the time spent moving the hand from one dial to the other. The time taken to travel between the dials depended on the precision of both the preceding and the following manipulations.

§ 1. Introduction

Ageing is usually accompanied by a decrement in motor performance. However, different aspects of the same task may not be affected equally by ageing (Miles 1931, Welford 1958). The primary aim of the present study was to investigate the differential effects of ageing on the parts of a simple repetitive motor task. A comparison was therefore made of the performance of two widely different age groups on a dial setting task. A secondary aim of the experiment was to replicate, using older subjects, a study dealing with the effects on movement durations of changing the precision requirements of different components of a task (Simon and Simón 1959).

§ 2. Method

Figure 1 pictures the dial setting task, the main elements of which have been described previously (Simon and Simon 1959). The subject's task was, using his right hand, to adjust two dials one after the other as rapidly as possible until each had been set 12 times. In order to set a dial, the subject had to rotate it approximately $\frac{1}{4}$ turn until the next white mark on the dial face was aligned with the target mark at the 12 o'clock position above the dial.

An electronic motion analyser (Smader and Smith 1953) recorded separately and automatically the durations of the four parts of the task. The analyser contained four precision timers which the subject activated by grasping and releasing the dials. The timers recorded the time per trial spent manipulating each dial and also the time per trial spent moving between the dials.

The two types of dials used in the experiment are also pictured in Fig. 1. Aligning Dial Type A with the target mark required a fine adjustment while aligning Dial Type B with the same target mark required only a much grosser adjustment. A light above each dial signalled when a correct setting had been made. The purpose of the signal lights was to maintain a constant standard of accuracy for all subjects.

Each subject performed with the four different dial arrangements shown in Fig. 2. Condition I involved gross manipulation of both dials. Condition II involved fine manipulation of the left dial and gross manipulation of the right dial. Condition III involved gross manipulation of the left dial and fine manipulation of the right dial. Condition IV required fine manipulation of both dials.

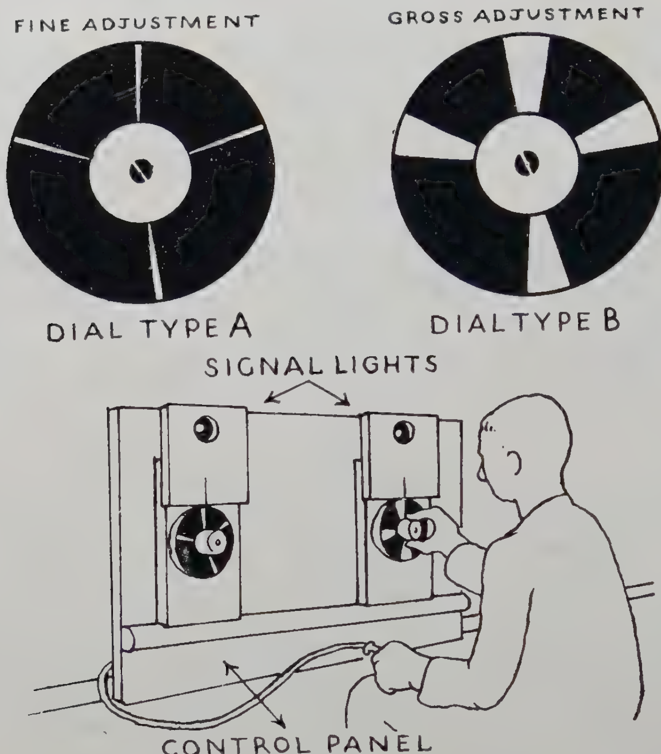

Figure 1. Sketch of dial setting task showing the two types of dials used. To align Dial Type A required a fine adjustment, and to align Dial Type B required a grosser adjustment.

Two groups of subjects were studied; a younger group of 24 naval ratings ranging in age from 18 to 34 (mean age 22·1 ; SD 3·9), and an older group of 16 subjects whose ages ranged from 59 to 85 (mean age 70·2 ; SD 6·0). All subjects were right-handed.

Each subject reported on four days during a five-day period. During the first session, he was assigned to one of the 24 possible sequences of the four experimental conditions shown in Fig. 2, and he continued to perform in this sequence during the next three sessions.

A session consisted of 12 trials, three on each of the four conditions. In each trial each of the two dials was set 12 times.

§ 3. Results

Each subject's performance during his fourth practice session was summarized in terms of the median duration for each part of the task under each experimental condition.

3.1. *Changes with Ageing*

Table 1 presents the mean time required for the older and younger groups to complete each part of the task under the four experimental conditions. It also shows the percentage increase in the time taken by the older group, compared with the younger on each component of the task. Note that the older group required an average of 45 per cent longer than the younger group to set the dials but only 14 per cent longer to perform the travel movements between

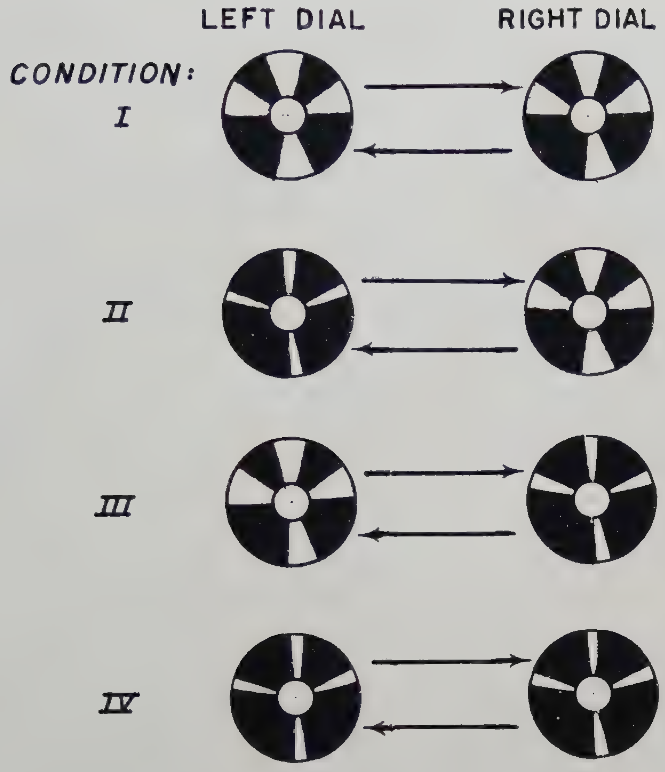

Figure 2. The four experimental conditions.

Table 1. Comparison of two age groups on duration of movements in a dial setting task performed under four experimental conditions.

Parts of task	Experimental condition	Types of adjustment before and after the movement concerned	Mean time per trial in seconds Younger group	Older group	Percentage increase with age
a. Left to right travel	I	Both gross	4·52	5·15	14
	II	Fine-gross	4·83	5·42	12
	III	Gross-fine	4·85	5·49	13
	IV	Both fine	5·03	5·61	12
b. Right to left travel	I	Both gross	4·53	5·26	16
	II	Gross-fine	4·80	5·56	16
	III	Fine-gross	5·02	5·80	16
	IV	Both fine	5·05	5·93	17
		Type of adjustment required			
c. Left dial manipulation	I	Gross	8·09	12·18	51
	II	Fine	15·37	23·43	52
	III	Gross	8·26	12·37	50
	IV	Fine	16·01	22·80	42
d. Right dial manipulation	I	Gross	8·13	12·24	51
	II	Gross	8·08	12·17	51
	III	Fine	17·16	23·56	37
	IV	Fine	17·82	22·77	28

dials. There appears to be no consistent difference between the increase associated with making a fine adjustment of the dial and that associated with making a gross adjustment.

3.2. *Effects of Changing Precision of Manipulations*

The performance of the older subjects during their fourth session was analysed to determine the effects on durations of the four parts of the task of varying the precision of the manipulations required. Four analyses of variance were performed, one for each part of the task ; i.e. left dial manipulation, right dial manipulation, left to right travel, and right to left travel. These analyses indicated that the durations of all four parts of the task were significantly affected ($p < \cdot 01$) by the precision with which the dials had to be set. To test specific predictions regarding the effects of varying precision, 10 t tests were computed between means listed in Table 1. The results of these tests are summarized in Table 2.

Table 2. Predicted relationship between movement durations and tests of observed differences

t test	Prediction*	Observed difference between means (seconds)	t
Travel movements tend to be slower when preceded by a fine than by a gross manipulation.			
1	aII > aI	0·27	1·94
2	aIV > aIII	0·12	1·24
3	bIII > bI	0·54	3·86*
4	bIV > bII	0·37	2·87*
Travel movements tend to be slower toward a fine than toward a gross manipulation.			
5	aIII > aI	0·34	4·51*
6	aIV > aII	0·19	1·95
7	bII > bI	0·30	3·94*
8	bIV > bIII	0·13	2·06
Travel movements tend to be slower between fine than between gross manipulations.			
9	aIV > aI	0·46	3·20*
10	bIV > bI	0·67	4·33*

*$p < \cdot 05$

* a refers to left to right travel and b refers to right to left travel.
Roman numerals refer to experimental conditions pictured in Fig. 2.

The first prediction tested was that with travel direction and precision of the *subsequent* manipulation held constant, travel movements will be slower when preceded by a fine than by a gross manipulation. The observed differences were all in the expected direction. They were significant for right to left travel (Tests 3 and 4) but not for left to right travel (Tests 1 and 2).

The second prediction stated that with travel direction and precision of the *preceding* manipulation held constant, travel movements will be slower toward a fine than toward a gross manipulation. The observed differences were again all in the expected direction. They were significant when movements from a gross to a fine adjustment were compared with movements between two gross adjustments (Tests 5 and 7) but not when movements from a fine to a gross adjustment were compared with movements between two fine adjustments (Tests 6 and 8).

The third prediction tested was that travel movements will be slower between two fine than between two gross manipulations. The observed differences were clearly significant (Tests 9 and 10).

3.3. *Discussion*

The most important suggestion arising from this study is that ageing has a much more marked effect on the manipulative than on the travel component of a task. Previous research has shown that the correlation between the durations of the manipulative and travel components is typically quite low (Rubin *et al.* 1952, Harris and Smith 1953) and that these two types of component are affected quite differently by practice (Wehrkamp and Smith 1952, Smith and Smith 1955).

The greater decrement of performance with ageing in the manipulative components cannot be explained by assuming that the precise movements required to set the dials are affected more by ageing than are the grosser body movements involved in moving the hand between the dials. If this was so, one would also expect that the increase of time for the fine setting of the Type A dial would be greater than that for the grosser setting of the Type B. Such was not the case with the present results.

For the same reason, the relatively greater difficulty experienced by the older group with the manipulative component of the task could not have been caused by a reduction of visual acuity with age.

The greater slowing of the manipulative component could have been a result of increased carefulness and a greater concern with accuracy on the part of the older subjects. Brown (see Welford 1958, Chapter 4) noted that these were probably the main causes of slowing in the performance of older subjects on a pointer positioning task. In the present experiment, although both age groups were given identical instructions with regard to speed and accuracy, the instructions could have been interpreted differently by the two groups.

Perhaps the most reasonable explanation for the greater change with age in the manipulative components of the task lies in the greater perceptual loading associated with this kind of movement. Subjects had to decide when a correct setting of the dial had been accomplished so that they could move toward the next setting. If the older subjects required a longer time to translate into action the data from the signal light indicating a correct setting, this would increase the time they remained in contact with the dials. This explanation agrees with the results of experiments by Szafran (1951), Leonard (1952) and Singleton (1954) which indicate that it is the interval required between the presentation of a signal and the start of the responding movement which tends to increase with age rather than the time required to complete the movement once it has begun.

The analysis of the effects of varying precision of manipulation on the duration of travel movements in older subjects generally confirms the results reported earlier for the younger group (Simon and Simon 1959) showing that the duration of a travel movement between two manipulations is dependent on the precision of those manipulations. In the present study, all the differences observed were in the predicted direction, although unlike the previous study, several of them fell short of an acceptable level of significance. This fact may well have been due to the smaller number of older people tested and the tendency for intra-individual variability to increase with age.

From the results of this and the other studies cited, it seems clear that a complete understanding of human skilled movements can be gained only through separate analyses of the different parts of a motor task. However,

when breaking down a task for purposes of analysis, the investigator must not lose sight of the fact that the components are interrelated and not independent.

This paper is based on data collected during 1955–56 while the author was a Fulbright research scholar at the University of Cambridge. Appreciation is expressed to Betty P. Simon, Alan T. Welford, and Karl U. Smith for their assistance and cooperation. The figures are reproduced from *The Journal of Applied Psychology* by permission.

Cette expérience concerne l'influence du vieillissement et les effets de la précision de manipulation sur la durée des mouvements. Deux groupes d'âges différents ont été comparés dans une épreuve de réglage de cadrans où la précision nécessaire pour ajuster les cadrans a été variée de façon systématique. Nous avons remarqué qu'avec l'âge vient une diminution dans le temps nécessaire pour régler les cadrans, tandis que la durée du mouvement entre les cadrans est moins influencée par l'âge. Le temps requis pour le trajet entre les cadrans dépend de la précision requise dans les manipulations et avant et après ce trajet.

Dies Experiment befasst sich mit dem Einfluss des Alterns und der Einwirkung der Einstellungspräzision auf die Bewegungsdauer. Zwei verschiedene Altersgruppen wurden bei einer Scheibeneinstellungsaufgabe, in der die Einstellungspräzision systematisch abgeändert war, miteinander verglichen. Mit steigendem Alter tritt eine merkliche Verlängerung der Zeit ein, die nötig ist, die Scheiben einzustellen, während der Einfluss des Alterns auf die Bewegungszeitspanne von Scheibe zu Scheibe nicht so gross war. Die Bewegungszeitspanne von Scheibe zu Scheibe kam eher auf die verlangte Präzision der Handhabungen an, die der Bewegung von Scheibe zu Scheibe voranging und folgte.

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THE PROVINCIAL SAFETY INSTITUTE OF ANTWERP

By the late C. C. Barnard and John R. Brown

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During the past hundred years in Europe and America there has been a general evolution of a concept of accident prevention and the need has been increasingly felt for the dissemination of information on the safest and best methods found in industrial practice. For this purpose centres and museums have been set up in many countries. Some, like the Industrial Health and Safety Centre in London, have attained a world-wide reputation. The establishment of this centre was originally proposed by the Home Office as long ago as 1911 but, because of the intervening war, it was not opened until December 1927 and given the name of The Industrial Safety, Health and Welfare Museum. Since 1951 the museum has been reorganized and in 1955 it was placed under control of the Ministry of Labour and National Service when its name was changed to the present title. A similar centre was opened in Birmingham in 1955.

Of particular interest is the less well known Provincial Safety Institute of Antwerp, Belgium (Provinciaal Veiligheids-instituut). Its origin goes back to 1926 when the Provincial Council of Antwerp discussed a proposal to found an institute for the instruction of employers and employees on the prevention of accidents. Two years later a Study Committee was appointed to investigate the establishment of a Safety Museum and at the first meeting the following proposals were made:

(i) That an intensive campaign on the basic principles of accident prevention should be carried out;

(ii) That a Safety Museum should be founded on the same lines as that already existing in Amsterdam;

(iii) That a site for the Museum be sought—the Health Institute in Antwerp being suggested as a provisional location.

By 1929 a grant of 100 000 francs had been obtained for the foundation of the museum and a working committee elected, and in October 1930 a competition for the best designs of Industrial Safety posters was held. During the years of the depression which then followed, however, the project was shelved but in November 1936 a Technical Committee was set up, and through its efforts an Exhibition of Industrial Safety was held at the Provincial Health Institute at Antwerp. This exhibition attracted a large number of visitors and rapid progress was made in the collection of material, etc., for the opening of a Safety Museum which was finally realized on 4 July 1942.

Simultaneously a series of lectures was commenced and later printed, in pamphlet form, as ‘ Doe het Veilig ’ (Do it Safely) in 1943.

The museum was closed in the early part of 1945 and reopened in September of the same year with new material obtained through the cooperation of the American and British Occupying Forces.

In February 1946 a new building was acquired in the centre of the city, and was fully occupied by the museum in 1954 when its name was changed to The Provincial Safety Institute of Antwerp.

The new building contains many exhibits of good industrial safety practices, personal and collective protective equipment, educational pictures and slogans designed to cultivate an interest in accident prevention in workers. There are model workshops, a large lecture theatre, and a wealth of information for the use of safety officers, foremen and supervisory staff.

Among the Institute's many activities, in addition to making available to manufacturers and workers advice on protective measures on industrial processes, may be mentioned the organization of visits of school children and students of technical colleges, and the publication in the Institute's " Journal " of articles on special studies.

The Institute is especially interested in the use of the different educational methods for the training of Safety Committees, Social Welfare Workers and Foremen, etc. There is also a mobile exhibition serving the same purpose.

Besides this Institute in Antwerp and the Centre in London, the following Institutes and Museums in Europe have permanent exhibitions concerned with the safety, health and welfare of the industrial worker. These are given with their location and date of origin, where known.

1. Musée Fédérale d'Hygiène industrielle et de Prévention des Accidents du Travail: Lausanne.
2. " Gewerbhygienische Sammlung in der Eidgenössischen Technischen Hochschule ": Zurich, 1883.
3. Stichting Het Veiligheidsinstituut: Amsterdam, 1889.
4. Bayerisches Arbeitsmuseum: later Das Bayerisches Landes-institut für Arbeitsschutz: Münich, 1900.
5. Musée de la Prévention des Accidents du Travail et d'Hygiène industrielle: Luxemburg, 1904.
6. Musée de Prévention des Accidents du Travail et d'Hygiène industrielle: later " Ecole des Arts et Métiers ": Paris, 1905.
7. " Social Utzällning ": later " Foreningen för Arbetarskydd ": Stockholm, 1906.
8. " Nepegeszeguyi Museum ": later Szakszervezetek Országos Tanácsa Munkávédelmi Tudományos Kuató Intézeti: Budapest, 1907.
9. " Technike Museum "; Prague, 1908.
10. " Tapaturmantor juntayhdistys ": Helsinki, 1909.
11. Technisches Museum für Industrie und Gewerbe: Vienna, 1910.
12. Esposizione permanente della Siccurezza del Lavoro e d'Igiene industriale: Milan, 1912.
13. Norsk Forening for Socialt Arbeid; later Utstillingen Vern Og Velferd: Oslo, 1914.
14. Udstillingen for Arbejderbeskyttelse: Copenhagen, 1919.
15. " A Museum of Industry and Safety ": Dorpat (Estonia), 1921.
16. " A State Institute of Industrial Health ": Moscow, 1925.

NEW DEVELOPMENTS IN ERGONOMICS TRAINING

DEPARTMENT OF ERGONOMICS AND CYBERNETICS

Loughborough College of Technology

The first Department of Ergonomics to be established in this country, devoted to teaching and research, has been set up at Loughborough College of Technology. So far as is known no comparable department is to be found in any other country. It is a cause of great satisfaction to all those interested in the future of Ergonomics that Dr. W. F. Floyd, of the Department of Physiology, Middlesex Hospital Medical School and formerly joint honorary secretary of the Ergonomics Research Society during the first five years of its existence, has accepted appointment as Head of the Department and will be taking up his duties at Loughborough in September 1960. Two further appointments to the academic staff of the new Department have been made so far. Dr. E. Edwards, of the University of Bristol and Nuffield Unit for Research on Employment of Older Workers, and Mr. P. T. Stone, of the Clothing and Stores Experimental Establishment, Farnborough, have been appointed Lecturers.

Dr. Floyd is planning to start a one-year full-time post-graduate course in Ergonomics in January 1961. Research in ergonomics will be encouraged, both on basic problems and on *ad hoc* questions directly related to immediate industrial needs.

ERGONOMICS AT CRANFIELD

It is also satisfactory to note that a Lectureship in Ergonomics has been established in the Department of Aircraft Economics and Production, The College of Aeronautics, Cranfield. Mr. W. T. Singleton has been appointed and has already taken up his duties. Mr. Singleton was formerly Head of the Ergonomics Department of the British Boot, Shoe and Allied Trades Research Association.

Mr. R. G. Lacey, formerly of the Ergonomics Department of Tube Investments and the Army Operational Research Group, has been appointed to the staff of the Cranfield Work Study School.

Research and teaching on topics related to Ergonomics have been proceeding at Cranfield for the last twelve years and it is now intended that these facilities should be expanded considerably. The differing training requirements for Service personnel, industrial specialists and work study engineers are being considered. A ten-week course for Military and Civil Service personnel is planned for January, 1961, to be followed by a one-year course for industrial specialists.

BOOK REVIEWS

Hawthorne Revisited : Management and the Worker, its Critics, and Developments in Human Relations in Industry. By H. A. LANDSBERGER. Ithaca, N.Y. : Cornell University, 1958. Cornell Studies in Industrial and Labor Relations, Vol. IX. Pp.132. $3.50.

BETWEEN 1927 and 1932 the Western Electric Company and Harvard University together carried out a series of social psychological and industrial psychological studies at the Company's Hawthorne (Chicago) Plant. The Hawthorne Studies began when industrial psychologists were largely going on the practical assumption that environmental conditions could be directly linked to end-behaviour (e.g. output) ; they were progressively led on to cover leadership, group and social influences so that, at the end, Landsberger sees " the authors demonstrating to industrial psychologists like themselves . . . that industrial relations factors could not be ignored even in the heartland of industrial psychology : in the investigation of reactions to lighting and rest pauses." Landsberger's analysis of the key place of the Hawthorne Experiments, allied with other trends, in a decisive change of character of industrial psychology is highly important for the historian of ergonomics. His precision here makes one wish that he had also traced the origin of the term ' Hawthorne Effect ' and defined its proper usage, whether to cover the application to the field of human behaviour of the general scientific fact that any act of observation has linkage with, and may therefore affect, the phenomenon observed ; or whether, more restrictedly, to cover the cases when the effect of observation is to induce behaviour which is (in some respect) ' better '—the reviewer prefers the more specific usage.

But ' Hawthorne ' quickly became one of the most potent legends in the fields of industrial administration and personnel management ; and a bitter controversy has been waged between the Elton Mayo school (linked with the term ' human relations ') and certain sociologists and economists interested in industrial relations. Landsberger examines both these developments in the light of a full analysis of the Hawthorne Studies, as they are reported in detail in *Management and the Worker* by F. J. Roethlisberger and W. J. Dickson (Cambridge, Mass. : Harvard University Press, 1939). This brings out how tenuous is the relation between the scientific data and conclusions reported in *Management and the Worker* and the more general writings of the ' human relations school ' supposedly based on the findings, and also the grounds for the attack. Landsberger indeed shows, and relates to their historical context, the limitations and weaknesses of the Hawthorne Studies ; under this evaluation, and stripped of secondhand accounts and controversy, the work stands revealed in full stature as a set of case-studies, a pioneer demonstration that empirical research within industry was possible, setting a high standard of objective and full presentation of data (so that it is still a rich source of comparative material), and touching—as much by the material presented as by its conclusions—upon most of the problem areas into which the field of human relations in industry is now breaking up.

Landsberger concludes " the authors of *Management and the Worker* need not hang their heads in shame, for the book is indeed a classic ". It contains, be it added, much directly relevant to the practice of ergonomics, material which can be better seen and appreciated after reading the present book. Last but not least, the quality of Landsberger's own book and the clarity of its style are fully worthy of its theme. R. G. STANSFIELD

Ergonomie. Ebauches Ltd., Neuchatel, Switzerland. Collection " Travail " Nr. 2, 1959. Pp. 48. S.fr. 9.

THE work study department of Ebauches Ltd., Neuchatel, Switzerland, have set out in this booklet the main points in the field of ergonomics. The content is presented in a brief and attractive form and should be especially useful for equipment designers and industrial engineers. We find in the foreword to this ' vademecum ' the following statement : " This booklet sets out the data so far established which should be taken into consideration for improving human conditions at the work place. The knowledge we have in this field is not yet great and is not well known in industry. The title of the booklet and part of its content will be surprising to many readers."

This surprising effect is indeed very well used and the readers will be compelled to look carefully at this booklet. There are no long descriptions nor discussions, but short and impelling rules illustrated by numerous striking figures and cartoon-drawings.

The booklet deals first in four chapters with the human body, sensory functions, movements, and comfort. In other chapters we find suggestions and rules for the facilitation of muscular work and of sensory and other psychomotor functions. E. GRANDJEAN (Zurich)

ERGONOMICS RESEARCH SOCIETY

PROCEEDINGS

A Meeting with the general theme "Ergonomics of Administration" was held on 27th November, 1959, at the Department of Management and Production Engineering, Brunel College of Technology, Acton, W. 3.

The following papers were delivered:

(1) "Administrative Work and Human Relations from the standpoint of an Experimental Psychologist", by A. T. Welford, The Psychological Laboratory, Cambridge University.

Little progress has been made so far in applying the human biological disciplines to the problems of administrative and white-collar work. There seem, however, to be considerable opportunities for using theories and approaches developed during recent years in experimental psychology. Of these four may be specially mentioned :

(*a*) The fact that discrimination, choice and decision-making take times which rise with level of fineness or complexity, means that we have *in principle* a method of measuring the load upon an executive by measuring the number and complexity of the decisions he has to make. It also implies that the range of decisions channelled through any one person should be restricted.

(*b*) Considerable economies of decision making may be achieved if procedures are analyzed into routines which can, with minor modifications, be brought into play in a wide variety of circumstances.

(*c*) It is insufficient to consider only the *average* load upon an individual : decisions may be called for at times which are determined not by the man making them but by external events or other persons. In these cases, the load at 'peak' periods may greatly exceed the average load.

(*d*) One of the most important yet also most fragile of human capacities is the ability to store data for short periods. On this depends not only a great deal of minute-to-minute retention of information, but also integrative activities such as problem-solving and complex thinking. The capacity of short-term memory is very limited, especially when data have to be carried over other activities. It seems to be essential for efficiency and reliability to try to 'build in' remembering devices into office equipment and routines.

Experimental psychology has also a contribution to make to the study of 'human relations' in industry. Problems in this area seem to arise from three types of cause :

(i) Conflicts of aim between different people
(ii) Irrational antipathies between persons
(iii) People and their actions impose demands and loads upon other people with whom they deal which are in several important ways analogous to those made at a shop-floor level by industrial jobs and machines upon operatives.

Very little is known which is relevant to the first two causes : the third appears to be ripe for development as a direct extension of existing knowledge of ergonomics.

(2) "The Medical Aspects of Administrative Work", by Dr. H. Beric Wright, Medical Research Unit, Institute of Directors.

There is increasing agreement that environmental and personality factors can play a significant part in the aetiology of certain diseases. If this is so, conditions like coronary thrombosis and hypertension come within the scope of industrial and environmental medicine.

Although there is virtually no factual information about the ergonomics of administration, an attempt was made to show that this was a field which might usefully be ploughed by people concerned with the human biological disciplines. An approach along these lines might be additionally useful because of the increasing need to understand the dynamics of stress and conflict, as an aid to dealing with psychosomatic disease.

Attention was also drawn to the need for liaison between research workers and industrialists in analyzing executive skills with a view to improving methods and conditions of administrative work.

(3) "Some Aspects of Morale in the British Civil Service", by Dr. Nigel Walker, Scottish Home Departments.

This talk described some of the results of an investigation carried out, partly by questionnaire, partly by interviews and partly by a study of available statistics, among the desk classes—i.e. the administrative, executive and clerical grades—of a number of Government Departments in 1958–9, while the author was Gwilym Gibbon Research Fellow at Nuffield College, Oxford.

The only aspects of the subject known as ‘ morale ’ which it was sensible to regard as ultimate aims of a personnel policy were efficiency and job-satisfaction ; and when considering the latter it was important to be clear whether we are doing so because it fosters efficiency or because it is an end in itself. There appeared to be no definite relationship between job-satisfaction and individual efficiency among desk-workers in the civil service (a result supported by certain other studies). If job-satisfaction has any effect upon efficiency it is probably indirect. Low job-satisfaction was associated with high wastage : both were found among young male clerical staff, and not only in the civil service. It was also associated with a slightly higher level of uncertified sick leave, but not to an extent which suggested conscious malingering.

One interesting by-product of the investigation was concerned with the effect of size of organization upon sick leave. Studies such as those made by the Acton Society Trust had suggested that the larger the organization the greater the average annual amount of sick leave taken by each employee : but a more rigorous study was needed to exclude the possible operation of factors such as geographical location and different risks of respiratory infection. It was also necessary to distinguish size of working unit, size of total working force on the same site (‘ size of office ’) and size of the whole organization, irrespective of location. Sick leave among civil servants showed no relationship with the size of their organizations (i.e. Ministries), but with the help of the Post Office a study was devised which suggested that it was related to ‘ size of office ’, even when differing infection risks were excluded. No satisfactory explanation of this relationship has been offered : it might be a ‘ morale effect ’, but there was no evidence to support this.

Job-satisfaction among desk-workers, both in certain Government Departments and in certain private companies, seemed to increase with time ; but further analysis is being carried out to see whether it is age, time in the organization or time spent on the current job that is the important factor. Job-satisfaction was also higher among higher grades : it seemed to be associated with the desk-worker’s estimate of the status of his job and with that rather vague concept, the ‘ interest of the work ’. Attitudes to the fairness or otherwise of one’s pay, on the other hand, had little to do with one’s enjoyment of one’s job, apart from a tendency among those who disliked their jobs to call themselves ‘ overpaid ’.

In contrast, very few of the factors studied seemed to have any connection with the individual’s efficiency, as measured by the reports of his superior officers. There seemed to be a tendency for efficiency to decline after the thirties ; and the more efficient showed slightly more pride in their organizations (but also a tendency to advise others against following their careers). There appeared to be no relationship between the individual’s own estimates of his capabilities and his superiors’ ratings.

It had also proved possible, however, to compare the collective efficiency of teams of clerical officers engaged on certain uniform and easily quantifiable tasks. The most efficient teams were not those whose members were older or younger, or had been doing this work longest, but those whose members had been in that team for the longest time. The supervisors were also studied and interviewed, one of the objects being to see whether those in charge of the best teams belonged to the democratic, ‘ employee-centred ’ type—as American investigators had found—or to the authoritarian ‘ production-centred ’ type. In this study the supervisors of the better teams appeared to be the firm ones who made a point of knowing their job ; the ‘ employee-centred ’ ones, who included most of the female supervisors, tended to have the less satisfactory teams.

(4) “ Speculations on Motives for Industrial Training ”, by R. A. F. Harcourt, Department of Management and Production Engineering, Brunel College of Technology.

The paper suggested that where a technically determined hierarchy exists in industry, the demands made upon members are determined, externally, by

(*a*) The number of people required to do the tasks.

(*b*) The technical complexity of each task.

(*c*) The technical interdependence of the tasks.

and ‘ internally ’ by the patterns of impulses operating within the people employed.

Discretion, judgment or choice becomes more onerous not only as their exercise becomes more frequent but also as the number of possibilities is extended. The range of possibilities is also increased because it is often not only necessary to obtain technical data but also to take account of the personal characteristics of the person giving it.

Training may be used realistically in an effort to decrease discretion by prescribing routines and making behaviour of people in the organization more predictable. It may also be used unrealistically by an administrator as a means of diverting attention from an unduly burdensome task of coping with anxieties induced by technological dependence on others. When training is suggested it is therefore important to analyze the allocation of technical tasks : there may be organizational factors tending to impede the efficient use

of technical personnel and if these, essentially social, factors can be dealt with, training may be found to be unnecessary.

(5) " Some Thoughts on Cybernetics and Organization ", by S. David M. King, Organisation and Training (Consultants) Ltd., London.

Our times are characterized on the one hand by the growth of large-scale organization, and on the other by an increasing preoccupation with the stresses playing on the individual in large concerns. In an organization which has reached some degree of stability, psychological stress can be resolved by the individual to some extent, through the accustomed organizational channels. But in an unstable organization, particularly in rapidly growing or recently amalgamated concerns, where procedures have not been sufficiently developed, the individual may have to take increased stress as a *person*. There is therefore a greater need today, for an understanding of organizational processes.

The relationship between an executive and his subordinate can be seen as the nucleus of organizational structure and process, and is sometimes called the nuclear command relationship. The operation of authority and responsibility in the nuclear command, can be viewed in cybernetic terms as a power circuit. Authority implies the discharge of power, and responsibility is the ' answering for ' that discharge of power. This notion opens up the possibility of viewing certain aspects of this ' power circuit ' in terms of control mechanisms of different kinds. For example, some executives use paper systems to control the flow of authority, while others use the fear of punishment. But both methods have the function of control.

On a larger scale, it is possible to view a whole firm as a network of open systems ; for instance, financial, technical and social systems. The operations of such systems can be described in terms of flow, and of control mechanisms.

The advantage of using cybernetic terms is that they present the possibility of eventually setting up dynamic criteria for organizational design and health, and for the diagnosis of organizational disorders. Such a body of knowledge could have an influence on the relief of individual executive stress and at the same time improve the effectiveness of large-scale organizations.

(6) " Mental Load Assessment : an Approach by Industry ", by A. Graham, Central Work Study Department, Imperial Chemical Industries Ltd., London.

Work study techniques have been used in I.C.I. for many years, including the use of work measurement for purposes such as plant manning, labour cost control, and financial incentive schemes. Unfortunately, the smaller the physical component of the activity, the greater the limits on the applicability of work measurement. In many chemical plants, particularly modern highly-instrumented plants, there is less emphasis on the quantity of physical work and more on the care and attention with which it is done. In 1957, I.C.I. conducted a field experiment to find some method of analyzing, in a practical way, the non-physical component of a process worker's contribution.

There were eight research teams composed of senior representatives of line management and specialists in labour management and work study. About forty such people were engaged full time on the experiment for a period of about four months. More than fifty complete jobs were studied, ranging from senior controlroom operation to simple manual tasks.

Because of lack of knowledge about the range of man's mental capacity, and the difficulty of measuring mental effort on a time-and-intensity basis such as is used in physical work measurement, it was decided to study the job and not the operator. The experiment was aimed at devising and testing a method of quantifying the mental load imposed by jobs on their operators, without regard to the mental effort which any given operator would have to expend in order to carry that load.

Six classes of mental load were defined, and each job was examined in considerable detail to isolate situations imposing one or more of these classes of load. The classes of mental load defined were those involved in :

1. An operation by which a variable in the plant or process was directly controlled.
2. Monitoring a variable, without direct control.
3. Recognizing that a desired value or condition of a variable had been achieved.
4. Judgment of acceptability against a standard, following inspection.
5. The use of the short-term memory.
6. Planning a sequence of activities.

In order to quantify the results, an arbitrary method of awarding points was devised for each classification. The number of points per occasion was adjusted for frequency per working shift, to give a score per shift for each activity.

While the above experimental approach revealed a considerable amount about the jobs themselves and the mental loads involved, it was too detailed and cumbersome to be of

value as a practical technique. It was necessary to devise a simpler approach, and to make improvements to the method of awarding points to the various activities.

A revised procedure recognized that, with the exception of short-term memory, the classifications of mental load had in common that they involved the taking of a decision by the operator. A one-class system of assessment considered decision-taking under five headings :

(i) The number of factors in the decision.
(ii) The complexity of comprehension of each factor.
(iii) The interdependence of pairs of factors.
(iv) The use of the short-term memory.
(v) The delay-characteristics of the process.

A new scoring procedure was devised, taking into account the lessons learned from the first part of the experiment. This allowed the computation of a points score per decision per occasion, and subsequently a score for the whole job over a complete working shift.

The total points scores allowed the jobs to be placed in an order of ranking of mental load. This ranking seemed to make reasonable sense when validated against the judgment of management and the research teams. Certain anomalies, however, suggested that the mental load of decision-taking was not always the complete mental load in a job. The concept of a background mental load was advanced. This load seemed to be related to the number and types of concurrent sources of information in the process, and could be said to be the load imposed on the operator by the exercise of disparate attention.

The experiment was done in order to explore means of solving a practical problem, and was of necessity less refined than the laboratory type of experiment on mental activities. In its own context, the experiment was successful in that it did a great deal to put the problem into perspective and to point the way to further work which could profitably be done.

ERGONOMICS RESEARCH SOCIETY

GENERAL RULES OF THE SOCIETY

1. The Society shall be called " The Ergonomics Research Society ".

2. The object for which the Society is established is, so far as by English law charitable, to promote learning and advance education in the subject of and with regard to the relation between man and the environment in which he works and particularly the application of anatomical, physiological and psychological knowledge to the problems arising therefrom, and in order to attain the foregoing object the Society shall have the following powers, namely :—

(*a*) To arrange for educational courses, lectures and examinations.

(*b*) To establish, carry on, promote, organise, finance and encourage the study, writing, production and distribution of books, periodicals, monographs and pamphlets and the publication of educational courses and lectures arranged under sub-clause (*a*) of this Rule.

(*c*) To establish, carry on, promote, organise, finance, equip and maintain libraries.

(*d*) To promote the formation of organisations for the purposes of any of the powers of the Society and to assist the organisations and their Managers, Committees and Officers as may be thought fit.

(*e*) To make provision for lectureships, bursaries, prizes and grants.

(*f*) To allot or lend moneys for the furtherance of the object of the Society.

(*g*) To undertake the Management of any Trusts or endowments and any scholarships and exhibitions for the furtherance of the object of the Society.

(*h*) To combine with Institutions or persons having a charitable object similar to that of the Society.

(*i*) To make suitable arrangements for carrying on the work of the Society and for meetings of the Society.

(*j*) To accept subscriptions, donations, devices, bequests and trusts.

(*k*) Subject in the case of moneys subject to or representing property subject to the jurisdiction of the Charity Commissioners to such sanction, if any, as may be required by Law, to invest the moneys of the Society not immediately required for the purposes of its powers in any form of investment of any nature or kind (including stocks or shares of any company) in any part of the World which in the opinion of the Society forms a desirable investment.

(*l*) To do all such other lawful and charitable things as are necessary for the attainment of the above object.

Provided That—

(i) The Society shall not support with its funds any object or endeavour to impose on or procure to be observed by its members or others any regulations, restriction or condition which, if an object of the Society, would make it a trade union ;

(ii) in case the Society shall take or hold any property subject to the jurisdiction of the Charity Commissioners for England and Wales or Ministry of Education, the Society shall not sell, mortgage, charge or lease the same without such authority, approval or consent as may be required by law, and as regards any such property the Officers of the Society shall be chargeable for such property as may come into their hands, and shall be answerable and accountable for their own acts, receipts, neglects and defaults, and for the due administration of such property ;

(iii) in case the Society shall take or hold any property which may be subject to any trusts, the Society shall only deal with the same in such manner as allowed by Law having regard to such Trusts ;

(iv) the income and property of the Society whencesoever derived shall be applied solely towards the attainment of the above object of the Society and no portion of the income and property of the Society whencesoever derived shall be paid or transferred directly or indirectly to the members of the Society but this proviso shall not prevent the payment in good faith of reasonable and proper remuneration or out-of-pocket expenses or both to any officer or servant of the Society or to any member of the Society in return for any services actually rendered to the Society nor shall this proviso prevent the payment of interest at a rate not exceeding 5 per cent per annum on money lent or reasonable or proper rent for premises demised or let by any member to the Society ;

(v) if upon the dissolution of the Society there remains after satisfaction of all its debts and liabilities any property whatsoever, the same shall not be paid to or distributed amongst its members, but shall be given or transferred to some other charitable institution or institutions having objects similar to the object of the Society and which shall prohibit the distribution of its or their income and property amongst its or their members to an extent at least as great as is imposed on the Society under or by virtue of proviso (iv) hereof, such institution or institutions to be determined by the members of the Society at or before the time of dissolution, or in default thereof by such Judge of the High Court of Justice as may have or acquire jurisdiction in the matter and if and so far as effect cannot be given to the aforesaid then to some charitable object.

MEMBERSHIP

3. The Society will consist chiefly of, and be governed exclusively by Ordinary Members, who alone will have power to elect members and officers, and to change the rules. The number of Ordinary Members shall not exceed one hundred and fifty or such larger number as the Council may from time to time decide, subject to confirmation by the Ordinary Members at the next Annual General Meeting.

4. Only those persons who work or have worked in the field of Ergonomics as defined in Rule 2, and agree in writing to become members, are eligible for election as Ordinary Members of the Society.

5. In addition to Ordinary Members, the Society may elect not more than ten Honorary Members. Persons of distinction who have contributed to the advancement of the aims of the Society are eligible for election as Honorary Members on the nomination of the Council.

6. Honorary Members shall have all the rights of Ordinary Members except that of voting.

7. Firms or Associations which have an interest in Ergonomics may become affiliated to the Society. Affiliated organisations may send two representatives to all Scientific Meetings of the Society, and they will receive one copy of all circulars, programmes and publications as sent to Ordinary Members.

NOMINATION AND ELECTION

8. Every nomination for Ordinary Membership of the Society shall give the full names and address of the candidate, also any degrees or diplomas which he/she may hold and the branch of work in which he/she is or has been engaged, together with a list of publications. Every candidate shall be recommended by not less than two members in the following terms :—

> A. B. having expressed a wish to join the Ergonomics Research Society we, the undersigned, from our personal knowledge, recommend him/her as a proper person to become one of its members.

9. Nominations made in the terms prescribed in Rule 8 shall be given in writing to the Honorary Secretary.

10. The Council shall, from the nominations submitted in accordance with Rules 8 and 9, prepare and cause to be submitted to any Meeting of the Society a list of approved candidates for election by the Ordinary Members of the Society at that meeting.

11. Nominations for Honorary Membership of the Society in accordance with Rule 5 shall be submitted to the Annual General Meeting of the Society.

12. At any meeting of the Society to elect members, if election by ballot be demanded by any member, one adverse vote in six shall exclude.

13. A person who has been elected a member of the Society shall be so informed and shall be sent a copy of the Rules. He shall not enjoy the privileges of membership until his first subscription has been paid.

14. Every application for affiliation to the Society shall give the full name, address and nature of business of the organisation. Applications will be considered by the Council which may accept or reject such applications.

15. The acceptance by the Council of an application for affiliation does not entitle the organisation concerned to describe itself as a member of the Society nor to use the Society's name in any way as to suggest that the Society approves of any product of or action by the organisation.

SUBSCRIPTIONS

16. The annual subscription for Ordinary Members shall be 3½ guineas, or such other rate as shall from time to time be determined by the Ordinary Members of the Society in General Meeting, in accordance with Rule 48.

Such subscription shall include receipt of one copy of each issue of the Journal published by the Society.

17. The annual fee for affiliation shall be 7 guineas.

18. The annual subscription and the annual affiliation fee are due on 1st January of each year and are payable in advance.

19. Every person elected as an Ordinary Member shall pay to the appropriate officer the annual subscription for the current year. Members elected after 30th September in any year shall not be called upon to pay another subscription until January 1st of the second year following that in which they were elected.

20. Any member whose subscription has not been paid for one year and has been informed in writing of the fact by the appropriate officer shall cease to be a member, unless in any particular instance, on the recommendation of the Council, the Society shall determine otherwise.

21. Resignation of membership shall be signified in writing to the appropriate officer, but the member so resigning shall be liable for the payment of his annual subscription for the current year, together with any arrears up to the date of his resignation.

22. The provisions of Rules 19, 20 and 21 shall apply also to organisations affiliated to the Society.

OFFICERS AND COUNCIL

23. The Officers of the Society shall consist of an Honorary General Secretary, an Honorary General Treasurer and such other number of Honorary Assistant Secretaries (not exceeding four) as may be recommended each year by the Council to the Annual General Meeting and confirmed by it. The allocation of the duties set out in Rules 38, 39 and 40 between these officers shall be at the discretion of the Council.

24. The business of the Society shall be carried on by a Council of members of the Society, consisting of the Officers and a Chairman of Council together with eight other Ordinary Members of the Society. The Editor of the Journal Ergonomics and one Associate Editor shall be *ex officio* members of the Council.

25. The officers, Chairman of Council and ordinary members of the Council shall be elected or re-elected annually.

26. Two auditors shall be elected annually ; they shall not be members of the Council.

27. No Honorary General Secretary or Honorary General Treasurer shall continue to hold office for more than seven consecutive years. No Chairman of the Council, Honorary Assistant Secretary or Ordinary Members of Council shall continue to serve for more than four consecutive years.

28. A quorum at a Council Meeting shall be five of whom one must be one of the Officers.

29. The Council shall have power to co-opt, until the next Annual General Meeting, not more than two other Members to serve as additional members of the Council. (Rule 24 not withstanding.)

30. The Funds of the Society shall be under the control of the Council who shall have the power to invest the same and to expend such funds for the promotion of the objects of the Society as they think fit.

The Council shall have power to appoint in writing two Trustees for the purpose of vesting in their names property, funds, deeds, documents of title and securities of the Society. Such Trustees shall be responsible to the Council at all times for the safe custody and proper keeping of all property, funds, deeds, documents of title and securities of the Society placed in their hands or under their control and shall produce the same for inspection whenever required to do so by the Council. The Council shall have power to remove such Trustees in writing and to appoint in writing Trustees to fill any vacancy caused by death, retirement or otherwise, and to appoint by writing additional Trustees as the Council may from time to time decide.

31. The Council may form Sub-Committees consisting of such Members of the Society as it thinks fit and may delegate any of its powers to such Sub-Committees.

32. It shall be the duty of the Council to propose to the Society for election or re-election names of members to fill the offices laid down in Rules 23 and 24. The names so proposed shall be submitted to the Ordinary Members of the Society six weeks before the Annual General Meeting. Other nominations for the Council made by Ordinary Members shall be seconded by two Ordinary Members and forwarded in writing to the appropriate officer at least one month before the Annual General Meeting, together with the consent of the nominee. If no fresh nominations are received, the Council's nominees will thereby be deemed to be elected. Otherwise, election shall be by ballot at the meeting.

33. Any vacancy occurring in the Council between Annual General Meetings may be filled by an Ordinary Member elected by the Council. The member so elected shall retire at the end of the year but shall be eligible for re-election by the Society at the next Annual General Meeting, Rule 27 notwithstanding.

THE HONORARY GENERAL SECRETARY

34. The duties of the Honorary General Secretary shall be to arrange the business of the Society in accordance with the directions of the Council, and to notify members of the time and place of meetings, to attend such meetings and also meetings of the Council and take minutes and to read these minutes and likewise any letters or reports.

35. The Honorary General Secretary shall prepare an annual report upon the activities of the Society for submission to the Annual General Meeting.

THE HONORARY GENERAL TREASURER

36. The Honorary General Treasurer shall have charge of the funds of the Society, receive sums due to it and pay such bills as are directed by the Council to be discharged.

37. The Honorary General Treasurer shall make up the accounts of the Society to the 31st December in each year and present at the Annual General Meeting an Income and Expenditure Account and a Balance Sheet duly certified by the Auditors.

THE HONORARY ASSISTANT SECRETARIES

38. The duties of the Honorary Assistant Secretaries shall be to keep an up-to-date list of members of the Society and publish this list from time to time to the members of the Society in accordance with the direction of the Council. The list shall indicate as Founder Members those Members who were present at the meeting convened at Oxford on 30th September, 1949, or who, being invited to attend, were unable to do so but expressed in writing their desire to become members of the Society.

39. The Honorary Assistant Secretaries shall send out nomination forms, receive nominations for membership and submit them to the Council, notify members of their election, collect subscriptions and maintain an account of them. They shall arrange speakers for, and venues of the scientific meetings, draw up programmes and submit them to the Honorary General Secretary and arrange meals and transport where necessary and receive bookings.

40. The Honorary Assistant Secretaries shall arrange all details of the Society's Conferences, arrange for the printing of programmes and abstracts and for their despatch to members and non-members. They shall receive registrations and any monies due. They shall keep an account of these and pay all bills arising as the result of a Conference. They shall make up the accounts to 31st December of each year and present them to the Honorary General Treasurer.

THE CONDUCT OF MEETINGS

41. Unless the Council decide otherwise, there shall be not less than three meetings in each year. One of these meetings shall be held in the first six months of the year and shall be the Annual General Meeting.

42. The ordinary meetings of the Society shall be scientific meetings. In addition at the Annual General Meeting, the administrative business of the Society shall be conducted. The Chairman of the Annual General Meeting or Special General Meeting shall be a member of the Council.

43. The Council shall make arrangements for the presentation and discussion of communications and demonstrations and all other matters relating to the expeditious conduct of scientific meetings.

44. At Annual or Special General Meetings a quorum shall be twenty persons or by proxy of which at least twelve shall be present in person.

45. Any Ordinary Member unable to attend an Annual or Special General Meeting may vote by proxy or by post by sending a completed and signed voting paper to one of the Secretaries before the day of the meeting. The Chairman of the meeting shall add such proxy and postal votes to those recorded by members attending in person.

46. The notice convening meetings shall give not less than twenty-one days' notice of the date of the meetings and the notice convening the Annual General Meeting shall give six weeks' notice. The Agenda for the Annual General Meeting shall be sent out three weeks before the date of the Meeting.

47. The Honorary General Secretary may call a Special General Meeting at the request of the Council or of ten members of the Society. Such a meeting shall be called so as to give at least one month's notice of the date of the meeting and the purpose for which it is called shall be explicitly stated in the notice convening the meeting ; no other business shall be transacted thereat.

48. The rules of the Society shall not be changed unless three-quarters of those voting are in favour of such change at an Annual or Special General Meeting. Notice of the suggested change must be given to the Honorary General Secretary at least one month before such Annual or Special General Meeting, and he shall notify all Ordinary Members of the suggested change at least three weeks before the meeting. Provided however that the provisions of Rule 2 hereof may only be changed in such a manner that the Society will, after any such change has been effected, be entitled to apply its income and property solely for objects which are by English law charitable.

49. Not more than one visitor may be introduced by each member of the Society at any ordinary meeting, provided due notice has been given to the appropriate officer beforehand. The Council shall have power to suspend or modify this rule.

PUBLICATION

50. A programme of each ordinary meeting shall be sent to all members at least seven days before the meeting. The programme shall include as far as possible the title of each Demonstration or Communication and, at the option of the author, may be accompanied by a brief account not exceeding 250 words. Copies of the programmes and abstracts of communications shall be preserved by the Honorary General Secretary. These accounts shall not be regarded as publications and may not be quoted without the author's consent.

51. No report of the proceedings at any meeting of the Society shall be taken or published unless the consent of the Council has been previously obtained.

INSTRUCTIONS TO CONTRIBUTORS

1. Articles for publication should be sent to the General Editor or to any Member of the Editorial Board.

2. Papers must be in English, French or German. Every paper must be accompanied by a brief summary, and contributors are asked if possible to supply summaries in all three languages.

3. Authors should submit a typescript, double-spaced on one side of the paper only. Footnotes should be avoided. Summaries, tables and legends for diagrams should be typed on separate sheets. Authors must ensure that the lay-out of mathematical and other formulae is clear. The typescript must represent the final form in which the author wishes the article to appear. The cost of any alteration in proof other than printers' errors may be charged to the author.

4. Diagrams should be drawn in black ink on white card or tracing paper. They should normally be sufficiently large to allow reduction in printing and the lines should therefore be bold. **All lettering should be up to draughtsmanship standard, suitably drawn in Indian ink to allow for reduction in size.** No charges are made for reproducing tables, diagrams or half-tone illustrations, but diagrams not suitable for reproduction without redrawing may be redrawn at the Author's expense.

5. References in the text should be indicated by author's name followed by the date. They should be listed alphabetically at the end of the paper in the style illustrated by the following examples:

BARTLETT, F. C., 1943, Fatigue following highly skilled work. *Proc. roy. Soc.* B, **131**, 247–254.

BEDFORD, T., 1948, *Basic Principles of Ventilation and Heating* (London: H. K. Lewis).

LE GROS CLARK, W. E., 1954, The anatomy of work. In *Symposium on Human Factors in Equipment Design* (Edited by W. F. Floyd and A. T. Welford) (London: H. K. Lewis). Pp. 5–15.

Abbreviations should be as in the *World List of Scientific Periodicals.*

6. **Consideration for publication will gladly be given to papers which have previously had a limited circulation as research reports.** Submission of a paper implies, however, that it has not been published and will not be published elsewhere without the permission of the General Editor and the Publishers. Copyright in material accepted for publication is retained by the Journal, and reproduction in whole or in part is forbidden except under the terms of the *Fair Copying Declaration* of the Royal Society or with the written permission of the Publishers.

7. Authors will receive 25 copies of their contributions without charge. Additional copies may be ordered at the time of returning proofs. Prices for additional copies may be obtained from the Publishers.

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